Turbo-Brayton Converter for Radioisotope Power Systems

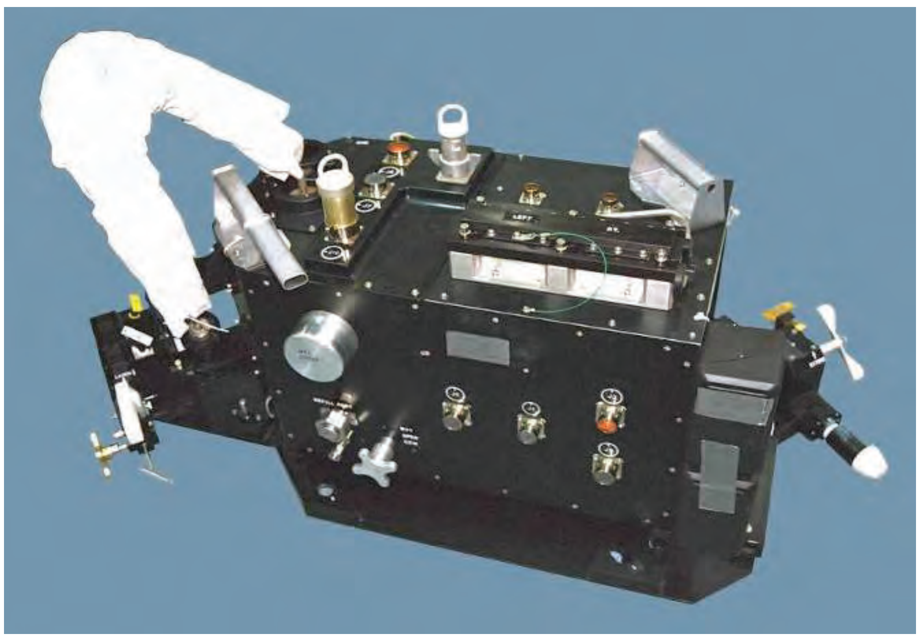
(Contract 80GRC17C0028)

RPS Community Review

8 May 2018

Background

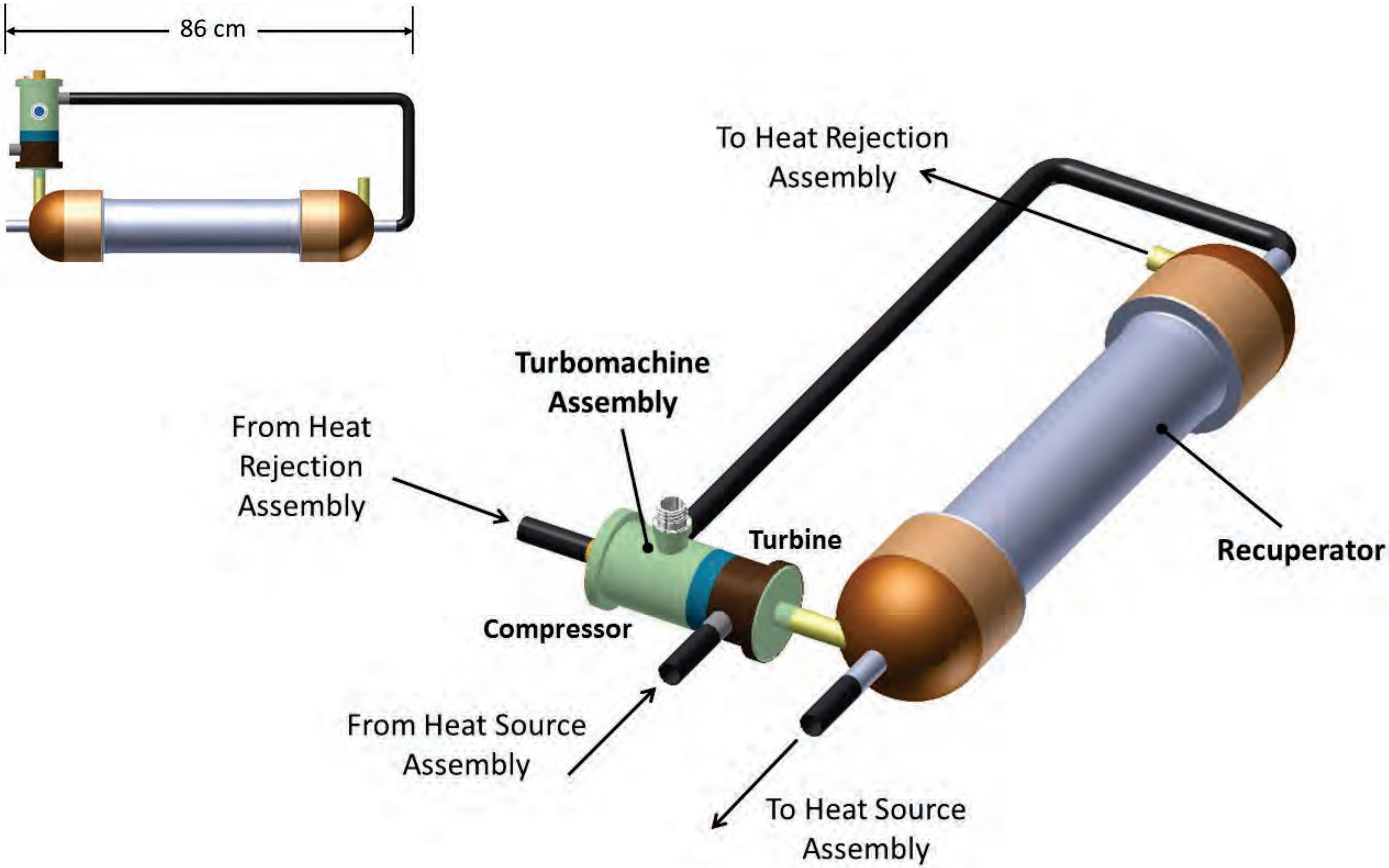
- Brayton converters are attractive for spaceflight applications
- Creare is an established provider of turbo-Brayton refrigerators and turbo-molecular vacuum pumps for space
- NASA is sponsoring technology adaptation for space power systems
- Creare, Rocketdyne, Sest, and UNM-ISNPS form a strong team



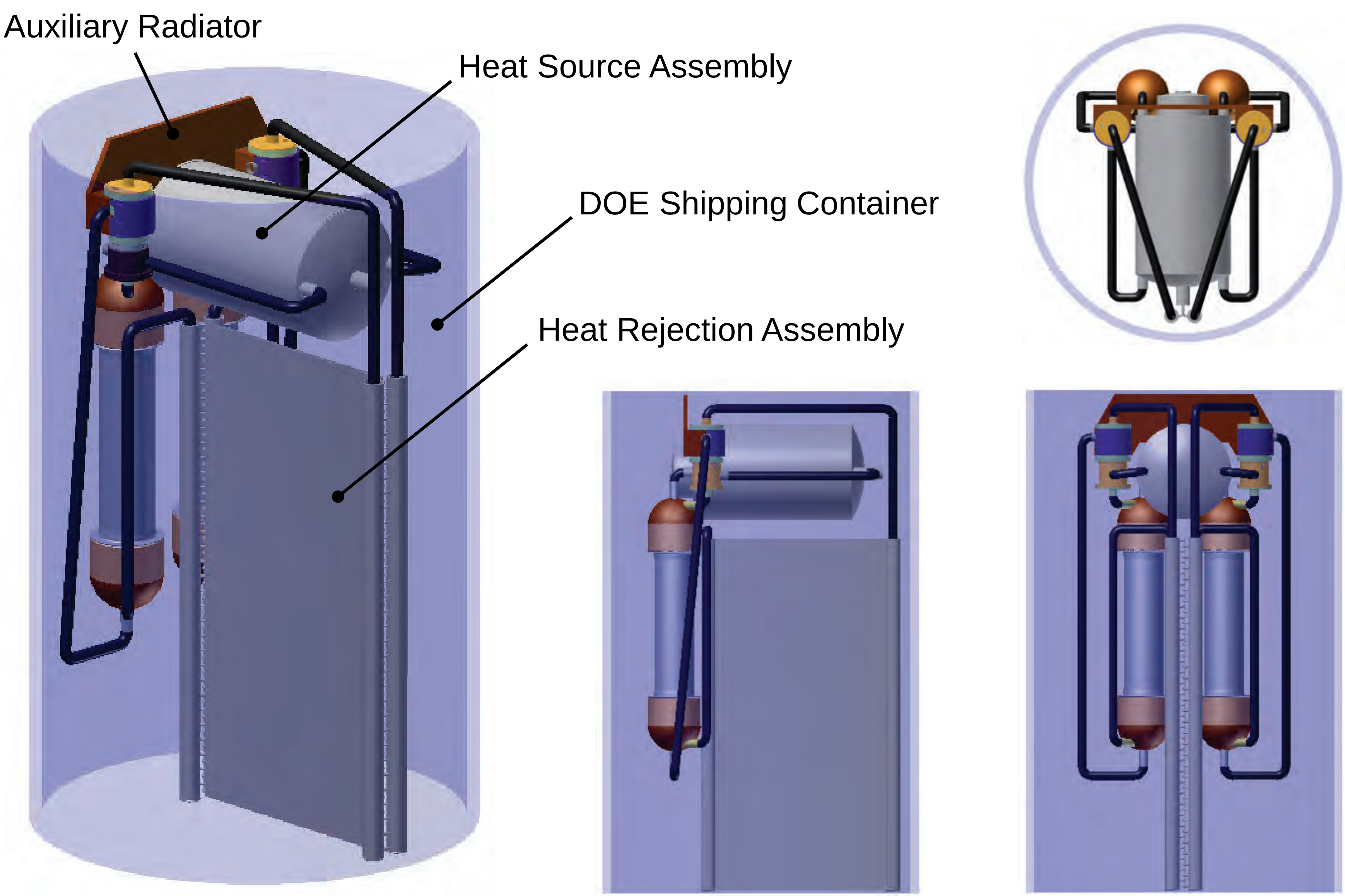
Brayton Cryocooler for Hubble Space Telescope

Vacuum Pumps for Mars Curiosity Rover

Converter


86 cm
To Heat Rejection Assembly
Turbomachine Assembly
From Heat Rejection Assembly
Turbine
Recuperator
Compressor
From Heat Source Assembly
To Heat Source Assembly

Creare/Rocketdyne Generator Concept



Agenda

- Creare Overview
- Design Overview
- Turbomachine
- Bearing Dynamic Analyses
- Recuperator
- Generator System Design (Rocketdyne)
- GPHS Thermal Analysis (UNM)
- Electronics and Controls
- Phase 2 Converter Assembly
- Reliability and Robustness Assessment (Sest)
- Conclusions

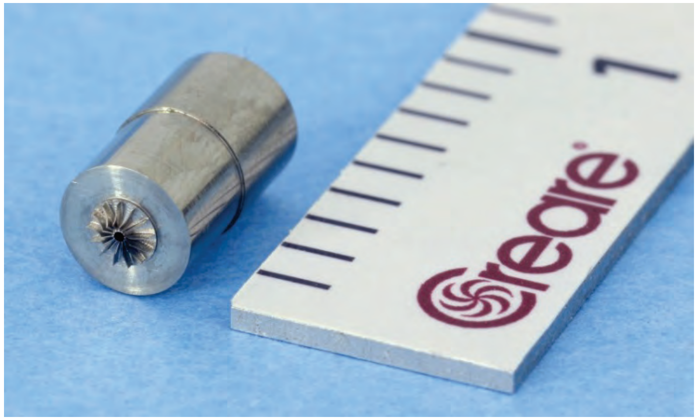
Creare Overview

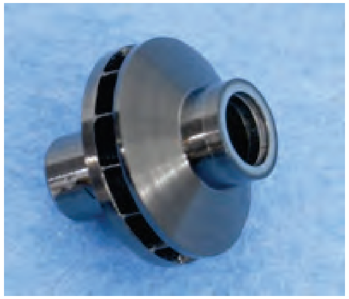
Creare Turbomachine History

- Turbomachines and thermodynamic systems have been a Creare focus throughout its 57-year history
- Early work devoted to industrial and commercial applications
  - Relatively large gas turbine engines
  - Turbochargers
- Gas bearing turboexpanders developed for DOE in early 1980s
  - Helium liquefiers for high-energy particle physics research
- Intense emphasis on turbo-Brayton cryocoolers for nearly 40 years
  - Many past and current projects
- Began developing miniature turbo-Brayton converter technology for NASA in 2001
  - 50-100 W_e radioisotope power systems
- Many other specialized turbomachine applications
  - High-energy lasers for missile defense
  - Radioxenon monitoring for nuclear test ban verification
  - Industrial uses

Creare Niches

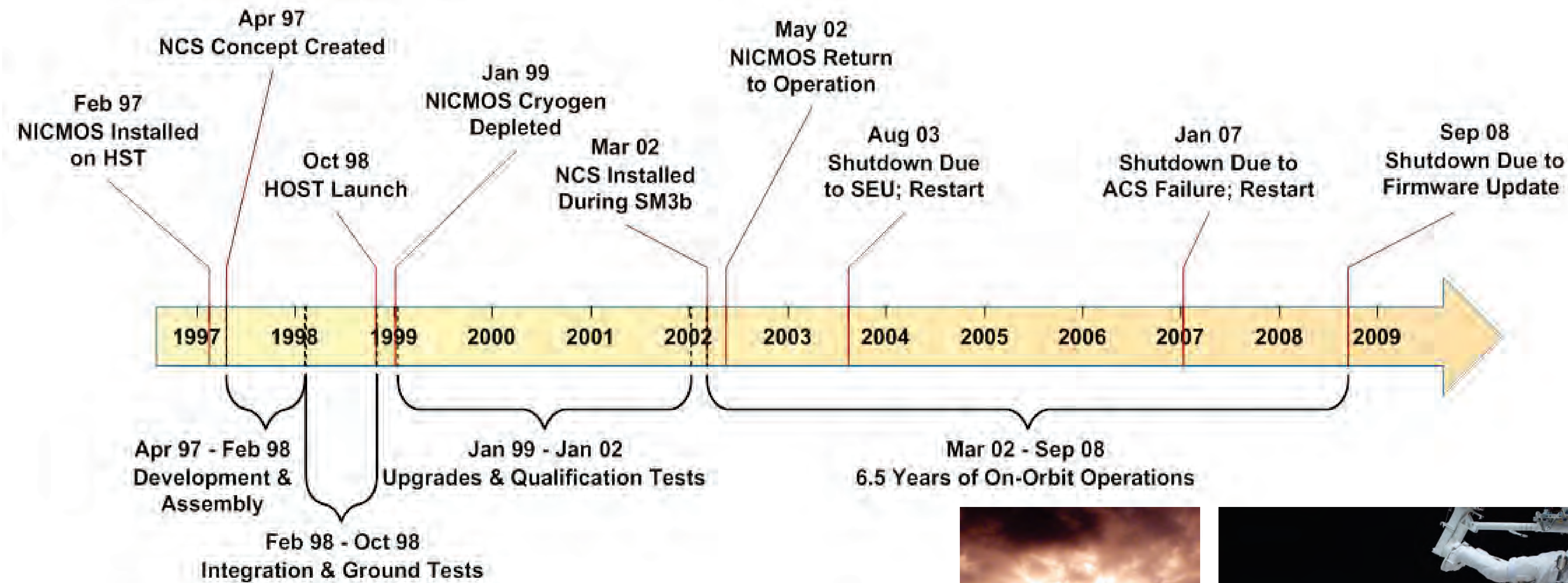
- **Closed-loop Brayton systems**
  - **Creare has focused on closed-loop Brayton systems, while most Brayton systems worldwide have open-loop configurations**
  - **Closed-loop systems are needed for space applications**
  - **Closed-loop systems can also provide high reliability in harsh terrestrial environments**
- **Small turbomachines**
  - **Required for low-power systems**
  - **Creare focus for several decades**
- **Compact heat exchangers**
  - **Important to minimize system size and mass**
  - **Creare focus for several decades**
- **High reliability**
  - **Essential for spaceflight programs**
  - **Beneficial for terrestrial applications**
  - **Gas bearings are a critical enabling technology**





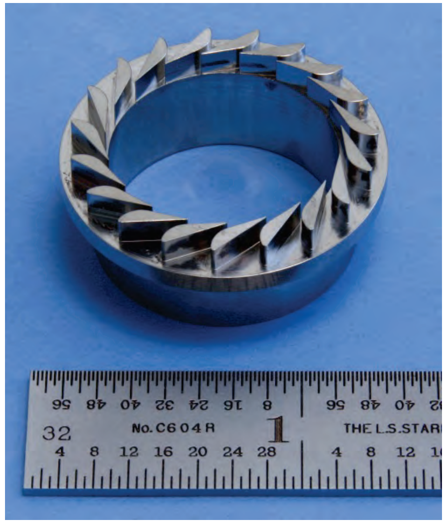
NICMOS Cooling System Timeline

Concept definition to delivery of cryocooler by Creare – 10 months
Delivery of cryocooler to flight – 8 months
Concept definition to installation on Hubble – 5 years
On-orbit operations – 6.5 years

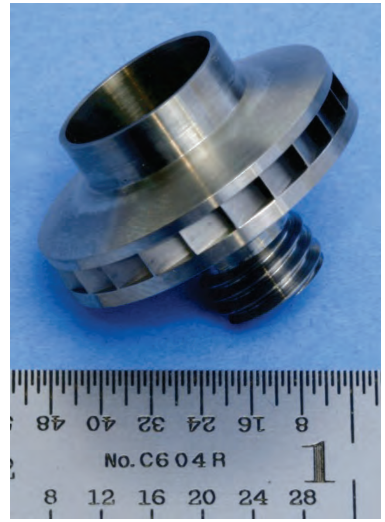


Turbomachine Technology

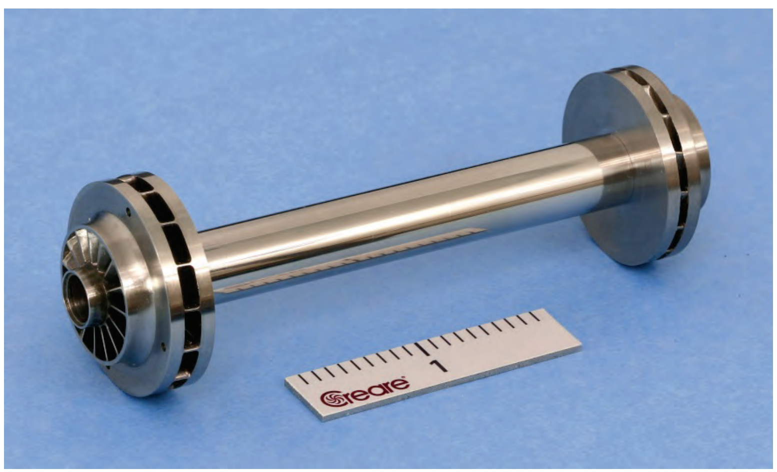
Rene 41 Turbine Rotor



Inconel Nozzle Ring



Shrouded and Unshrouded Compressor Impellers



Turbomachine Assembly for Brayton Power System
(Turbine, Compressor, and Internal Permanent Magnet)

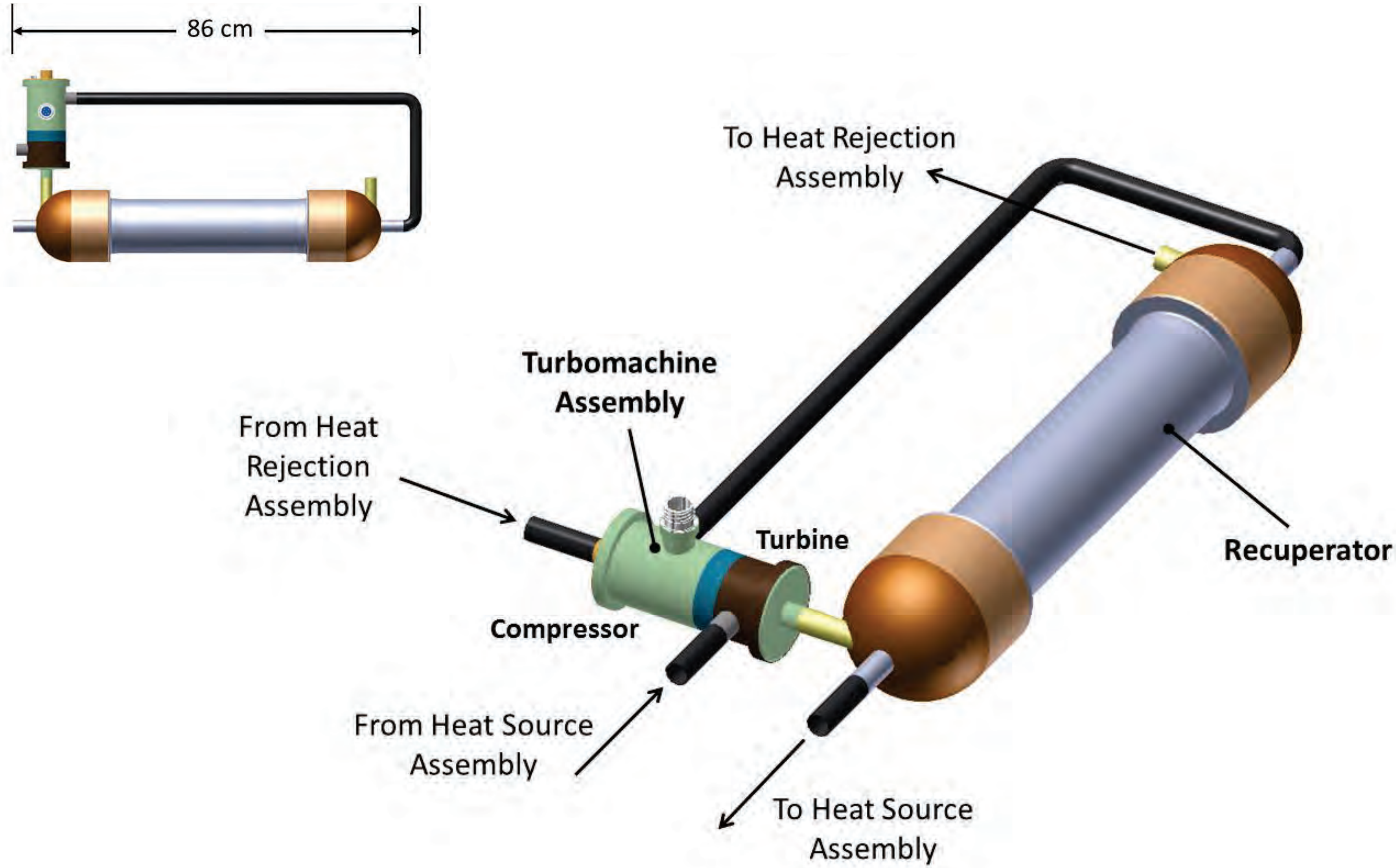
Turboalternator for Organic Rankine Cycle

Design Overview

Brayton Characteristics

- **High efficiency**
  - Limits size of heat source and heat rejection system
- **High specific power**
  - Facilitates launch vehicle packaging and reduces launch costs
- **Efficiency and specific power scale favorably as power level increases**
- **High reliability**
  - One moving component with non-contact gas bearings and clearance seals
  - No wear mechanisms, lubrication, or maintenance requirements
- **Long life**
  - Limiting factor is high-temperature material creep
- **Assembly can be packaged to utilize available space**
  - Discrete components connected by tubing/ducting
  - Customizable heat exchanger dimensions
- **Continuous gas flow can communicate directly with heat source and heat rejection surfaces**
  - Can eliminate heat pipes, conductive links, and intermediate flow loops required for other converter technologies
- **Vibration-free operation**
  - No need for vibration cancelling devices, control methods, or system configurations

Converter


86 cm
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Design Summary

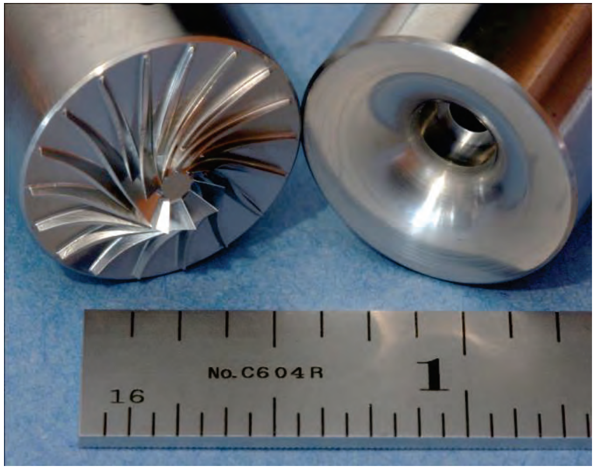
- **Predicted AC electric power is 355 W**
  - **Middle of range specified by NASA (200-500 W_e generator)**
    - **Brayton efficiency and specific power improve as power level increases**
  - **Practical power level for bearings with spaceflight heritage**
  - **Fixed planar radiator panels fit within DOE shipping container**
- **Predicted converter efficiency is 26.3%**
  - **Does not include AC-to-DC conversion losses**
  - **Does not include heat leak to environment**
- **Predicted converter specific power is 21.6 W/kg**
- **Selected 730°C for turbine inlet temperature**
  - **Provides high efficiency with acceptable creep life**
- **Conceptual generator design is similar to Low Power DIPS**
  - **Leverages prior Rocketdyne design effort**
  - **Enables two converters to operate at approximately half power or one to operate at full power**
    - **Converters hermetically isolated from each other with independent gas charges**
  - **Specified six GPHS Step 2 modules**
- **Heritage components, materials, and fabrication processes selected**

Heritage Summary

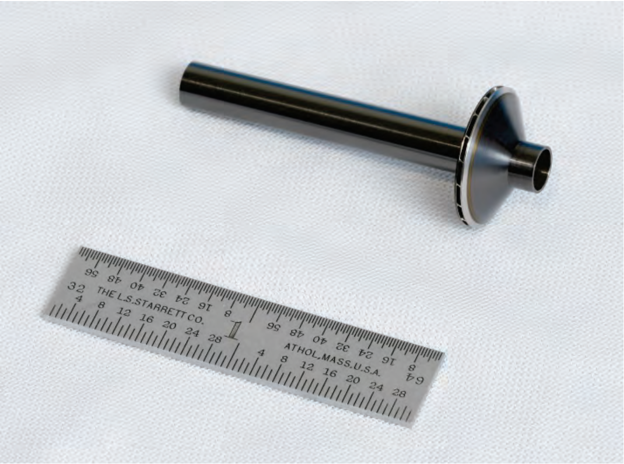
Heritage Summary for Key Elements in Converter	
Component	Heritage Summary
Journal Bearings	Journal bearings were space qualified for the NCC program; Compressor bearings in NCC on HST have same design and size.
Thrust Bearing	Space qualified version in NCC on HST is 20% smaller; Size specified for converter has been demonstrated in four 500-W_e compressors; Converter design has dedicated thrust disk
Compressor Impeller	Space qualified version in NCC on HST is 20% smaller; Size specified for converter has been demonstrated in four 500-W_e compressors
Turbine Impeller	Smaller version of impeller fabricated for prior project
Alternator/Motor	Same features as space-qualified version in NCC on HST, but outer diameter for converter is greater
Turbomachine Assembly	Similar version of other turbomachines fabricated for prior projects
Recuperator Assembly	Similar version of five units fabricated for NASA Contract NNC14CA15C; Converter version has larger frontal area and shorter length but same tube size, wall thickness, and tube spacing

500 W_e Compressor

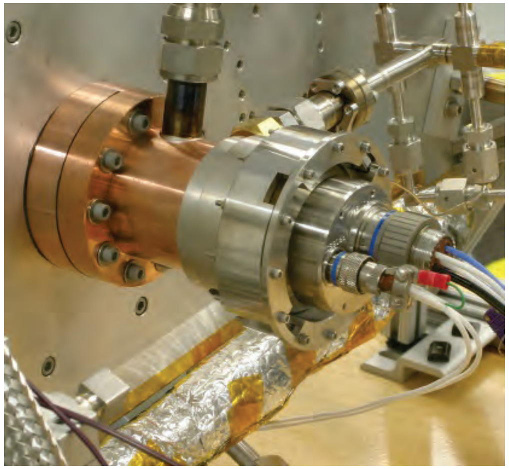
- Heritage source for bearings, compressor impeller, and alternator
- Impeller diameter is 19 mm (0.75 inch)
- Shaft diameter is 6.4 mm (0.25 inch)
- Rotor speed is 6,300 rev/s (380,000 rpm)
- Four built previously
- Several others built with same journal bearings and 15 mm (0.60 inch) impeller diameter
  - Compressor for NICMOS Cooling System on HST (400 W_e at 438,000 rpm)



Impeller Components



Rotor Assembly



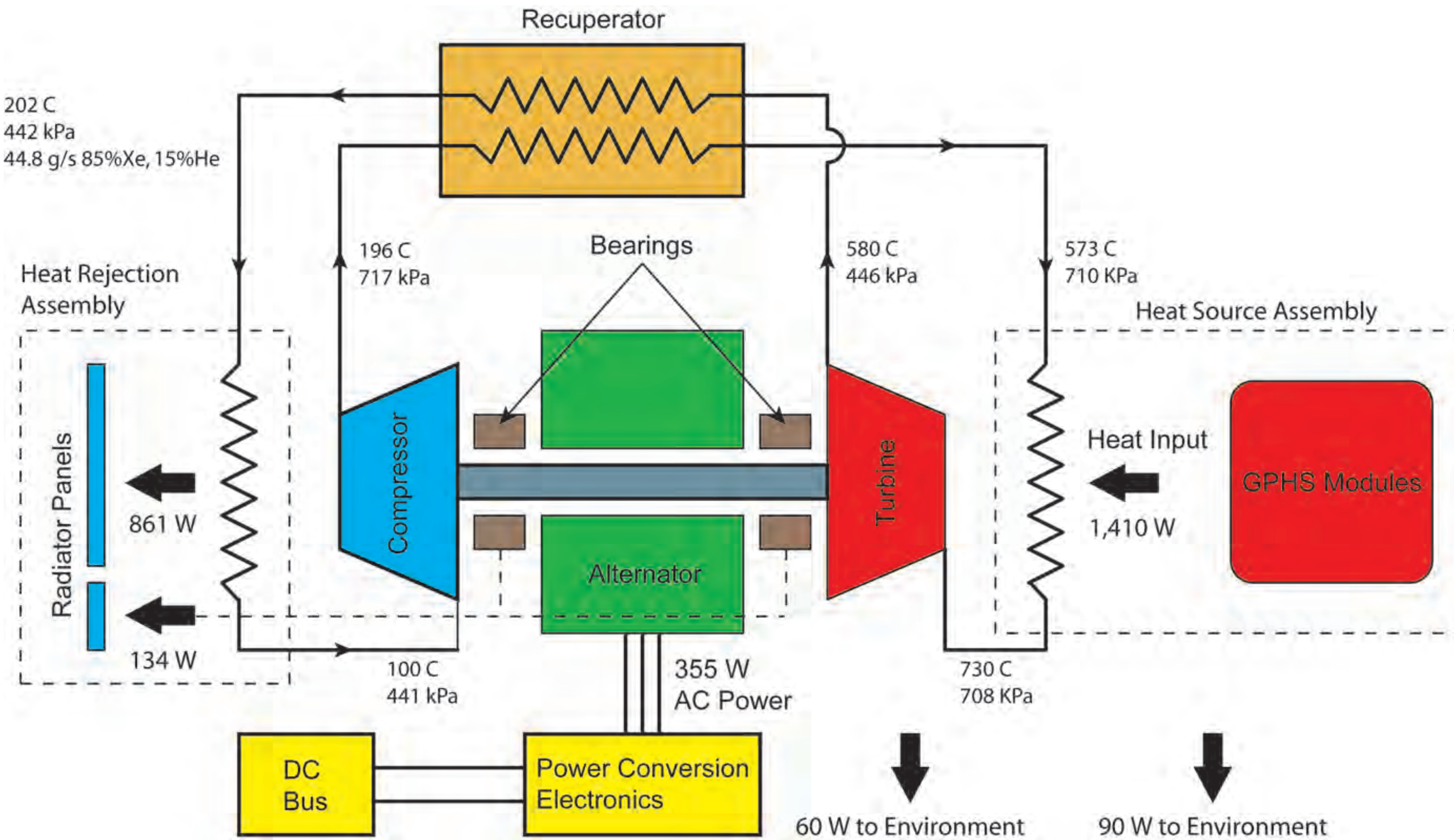
Compressor Assembly

Creare

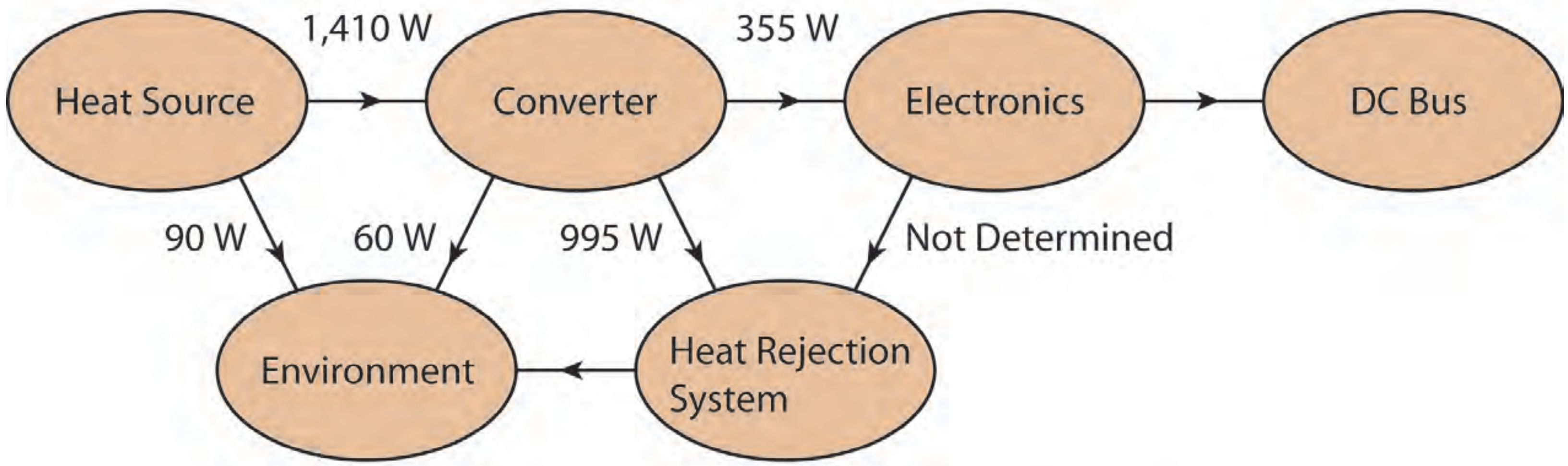
Reliability Demonstrations

Hardware Description	Demonstration
Durability test rig (1982-1996) • 3.2 mm shaft • 11,000 rev/s	• 123,000 hours (14 years) in filtered air at 300 K • 2,600 start/stop cycles during initial 10-year period with no maintenance
Turboexpander start/stop tests (1987) • 3.6 mm shaft	• 10,000 start/stop cycles in helium at 300 K • No anomalies or wear detected
Induction-motor compressor and inverter (2005) • 6.4 mm shaft	• 10,000 start/stop cycles in neon at 300 K • No anomalies or wear detected
5 W, 65 K Engineering Model cryocooler (1996-2000) • Compressor at 6,500 rev/s • Turboexpander at 8,500 rev/s • Single-stage CCE with manual controls	• 30,000 hours overall at nominal operating conditions • Known diffusion of moisture through O-ring seals caused minor performance degradation
Low-temperature cryocooler (2002-2003) • Two compressors in series at 9,200 rev/s • Dual-temperature turboalternator • Brassboard electronics	• 6,500 hours overall with no performance degradation • Temperatures down to 17 K
Orientation testing (2007) • Induction-motor compressor • Permanent magnet turboalternator	• 500 to 1,000 start/stop cycles in neon in each of four orientations • Ambient and 80 K tests for turboalternator
NICMOS circulator and inverter (1999) • 3.6 mm shaft	• 2,000 start/stop cycles in 300 K and 80 K neon • Flight unit and qualification units tested and inspected • No anomalies or wear detected
NICMOS cryogenic system (1998-2008) • Induction-motor compressor • Permanent magnet turboalternator • Cryogenic circulator • Cryocooler electronics	• 2 shuttle launches and one landing • 1,900 hours of ground testing • >200 start/stop cycles during ground testing • ~6.5 yrs operating time on Hubble Space Telescope

Brayton Cycle Schematic



Power Flow Diagram



Converter Efficiency = 355 W / (1,410 W - 60 W) = 26.3%

Critical Parameters

Critical Parameters for Converter Design		
Parameter	Full-Power	Half-Power
Working Fluid (Molar Composition)	85% Xe, 15% He	85% Xe, 15% He
Mass Flow Rate	44.8 g/s	31.1 g/s
Compressor Inlet Temperature	100°C	100°C
Turbine Inlet Temperature	730°C	730°C
Compressor Inlet Pressure	441 kPa (63.9 psia)	441 kPa (63.9 psia)
Compressor Pressure Ratio	1.63	1.36
Turbine Pressure Ratio	1.59	1.34
Rotor Speed	164,000 rpm	126,000 rpm
Compressor Efficiency	79.9%	80.6%
Turbine Efficiency	87.3%	85.6%
Alternator Efficiency	95.6%	96.0%
Recuperator Thermal Effectiveness	98.4%	98.5%
Number of GPHS Modules	6	6
GPHS Heat Generation Rate	1,500 W	1,500 W
Heat Leak Rate from HSA to Environment	90 W	90 W
Heat Input Rate to Converter	1,410 W	705 W
Heat Leak Rate from Converter to Environment	60 W	60 W
Heat Leak Rate from Warm to Cold End of Turbomachine	40 W	40 W
Turbine Power	1,227 W	548 W
Compressor Power	825 W	348 W
Bearing and Alternator Fluid Drag Losses	32 W	16 W
Alternator Electromagnetic Losses	16 W	7 W
Primary Radiator Heat Rejection Rate	861 W	382 W
Auxiliary Radiator Heat Rejection Rate	134 W	86 W
Unregulated AC Electric Power	355 W	177 W
Conversion Efficiency	26.3%	27.4%
Specific Power	21.6 W/kg	10.8 W/kg

Different Heat Rejection Temperatures

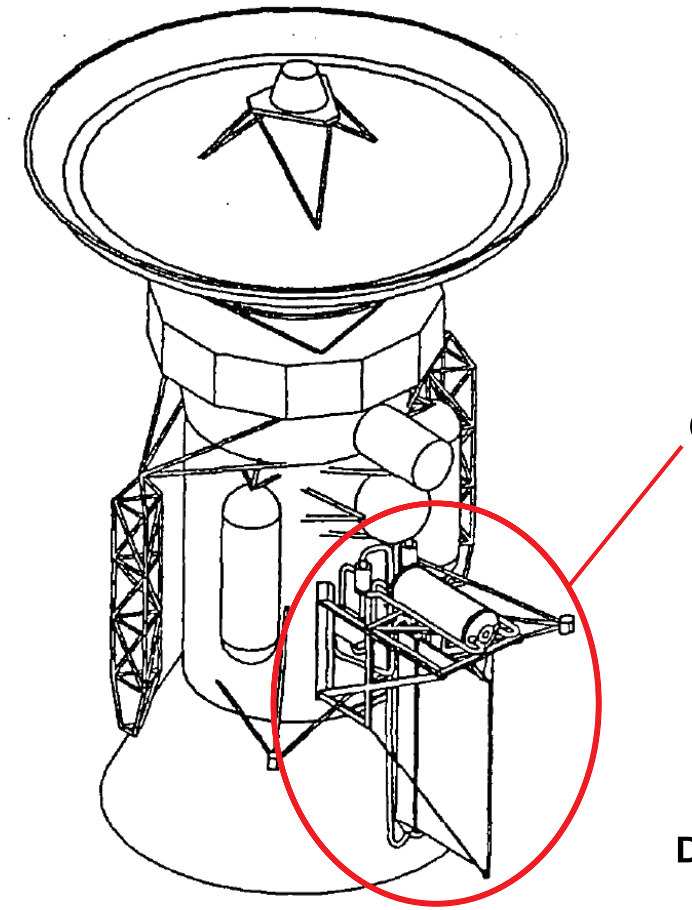
Critical Parameters for Different Heat Rejection Temperatures		
Parameter	Minimum Heat Rejection Temperature	Maximum Heat Rejection Temperature
Working Fluid (Molar Composition)	85% Xe, 15% He	85% Xe, 15% He
Mass Flow Rate	46.6 g/s	43.8 g/s
Compressor Inlet Temperature	20°C	175°C
Turbine Inlet Temperature	730°C	730°C
Compressor Inlet Pressure	441 kPa (63.9 psia)	441 kPa (63.9 psia)
Compressor Pressure Ratio	1.63	1.64
Turbine Pressure Ratio	1.59	1.60
Rotor Speed	142,000 rpm	184,000 rpm
Compressor Efficiency	81.1%	78.9%
Turbine Efficiency	82.3%	88.8%
Alternator Efficiency	93.2%	96.6%
Recuperator Thermal Effectiveness	98.4%	98.4%
Number of GPHS Modules	6	6
GPHS Heat Generation Rate	1,500 W	1,500 W
Heat Leak Rate from HSA to Environment	90 W	90 W
Heat Input Rate to Converter	1,410 W	1,410 W
Heat Leak Rate from Converter to Environment	60 W	60 W
Heat Leak Rate from Warm to Cold End of Turbomachine	40 W	40 W
Turbine Power	1,203 W	1,243 W
Compressor Power	658 W	1,005 W
Bearing and Alternator Fluid Drag Losses	24 W	40 W
Alternator Electromagnetic Losses	35 W	7 W
Primary Radiator Heat Rejection Rate	730 W	1,014 W
Auxiliary Radiator Heat Rejection Rate	135 W	145 W
Unregulated AC Electric Power	486 W	191 W
Conversion Efficiency	36.0%	14.2%
Specific Power	29.6 W/kg	11.6 W/kg

Masses

Converter Masses	
Component	Mass
Recuperator	10.1 kg
Turbomachine	5.6 kg
Tubing	0.7 kg
Total	16.4 kg

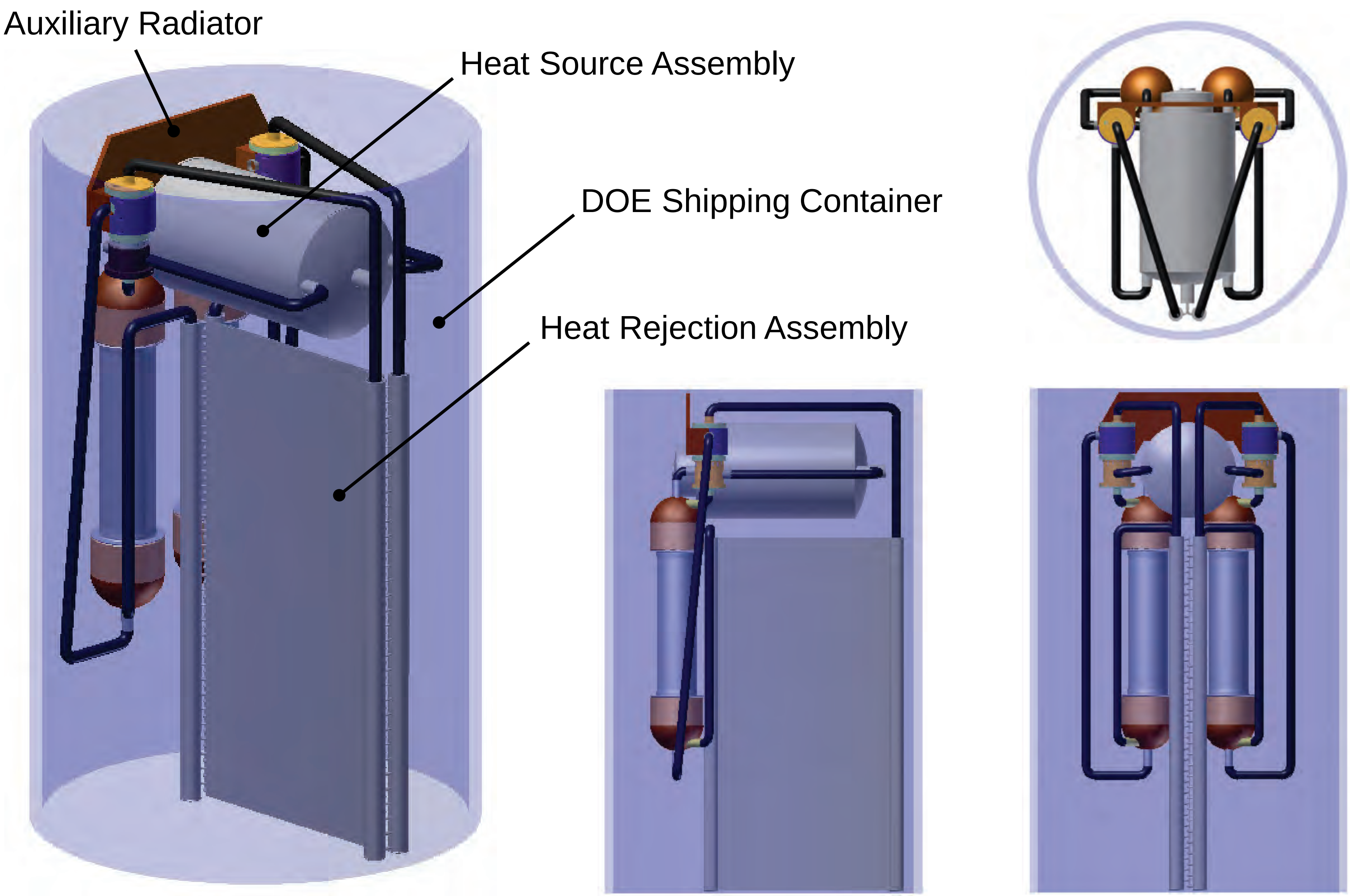
Conceptual Generator System Design

Creare/Rocketdyne design mimics DIPS configuration for JPL Mariner Mark II spacecraft with fixed two-sided radiator



DIPS integrated with MMII Spacecraft
Aerojet Rocketdyne

Creare/Rocketdyne Conceptual Design



Requirements, Goals, Compliance

Requirements, Goals, and Compliance			
Category	Requirement	Compliance	Verification
Design Life	20 years continuous operation at full power	Phase 2 converter designed and built to exceed 20 year life	Phase 1 analyses
Converter Power Output	Enable 200-500 W_e generator	Predicted alternator power is 355 W_e	Phase 1 analyses, Phase 2 test
Start-Stop Cycles	150 cycles with no impact	Prior Creare turbomachines have demonstrated 10,000 cycles	Phase 1 similarity assessment, Phase 2 test
Launch Vibration	No impact after exposure to launch acceptance vibration testing while operating	Phase 2 converter designed and built to satisfy requirement	Phase 1 analyses, Phase 2 risk-reduction test with existing Creare compressor,
Static Acceleration	Tolerant to 5 g for 5 days and 20 g for 1 minute in all axes while operating	Phase 2 converter designed and built to satisfy requirement	Phase 1 analyses,
Performance Degradation	Output power decrease < 0.5%/yr for constant heat input	No performance degradation mechanism identified	Phase 1 assessment

Requirements, Goals, Compliance

Requirements, Goals, and Compliance			
Category	Requirement	Compliance	Verification
Thermal-to-Electric Conversion Efficiency	Requirement ≥ 24% Goal ≥ 28%	Predicted efficiency is 26.3%	Phase 1 analyses, Phase 2 test
Partial-Power Operation	Goal ≥ 20% efficiency when thermal input power is 50%	Predicted efficiency is 27.4%	Phase 1 analyses, Phase 2 test
Hot-End Operating Temperature	< 1,000°C	Design value is 730°C	Phase 1 decision
Cold-End Operating Temperature	≥ 100 °C to meet efficiency goal; Capable of 20-175°C	Phase 2 converter designed and built to satisfy requirement	Phase 1 analyses, Phase 2 test
Thermal Energy Input	Must accept heat from integer number of GPHS-Step 2 modules	Six modules specified	Phase 1 analyses, Phase 2 simulation
Atmospheric Environment	Capable of operation in vacuum and several non-vacuum environments	Phase 2 converter designed and built to satisfy requirement	Phase 1 analyses, Phase 2 test in ambient Earth environment
Radiation	No performance impact after exposure to 300 krad	Prior Creare assessments indicate no impact	Phase 1 similarity assessment
Electromagnetic Interference (EMI)	DC < 100 nT at 1 m; Minimize AC	Phase 2 converter designed and built to satisfy requirement	Phase 1 assessment,

Requirements, Goals, Compliance

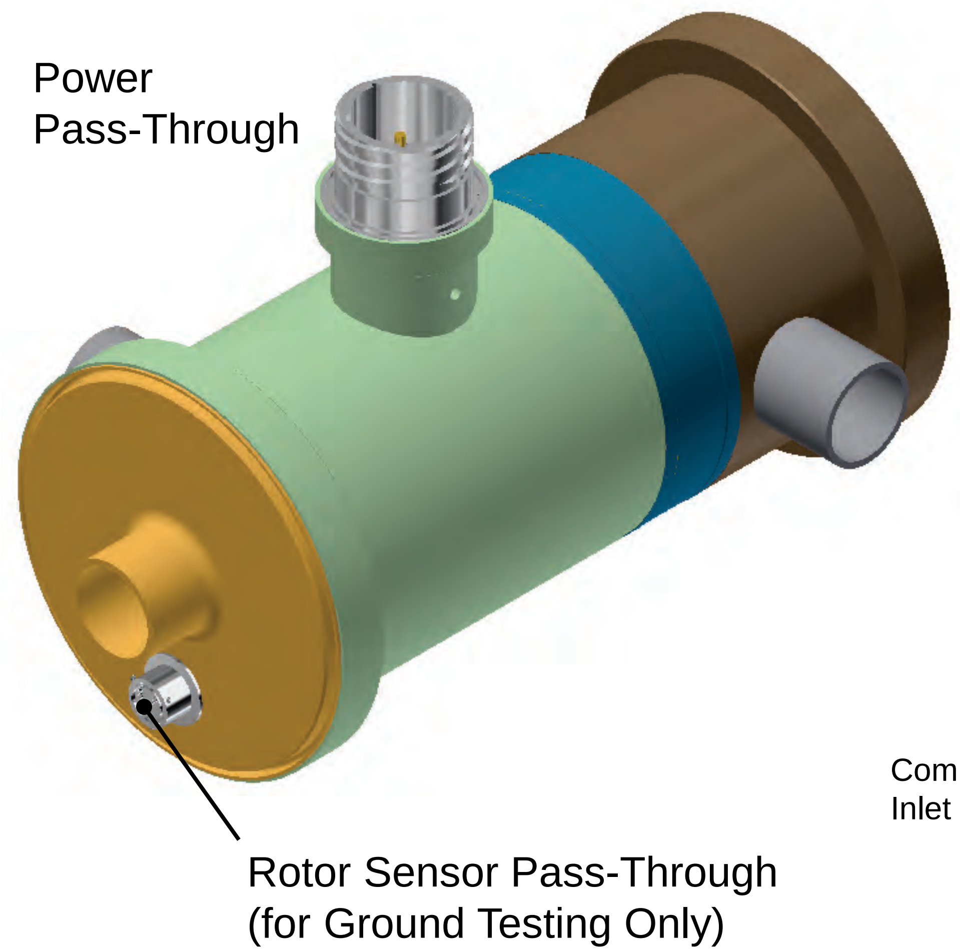
Requirements, Goals, and Compliance			
Category	Requirement	Compliance	Verification
Autonomy	No commanded adjustments required	Design is completely autonomous	Phase 1 design, Phase 2 test
Loss of Electrical Load	Tolerate loss of user load via shunt resistor (requirement) Tolerate loss of user load for 10 seconds without shunt (goal)	Autonomous shunt regulator will dissipate full converter power when necessary, design <u>may</u> tolerate loss of load without shunt	Phase 1 design, Phase 2 test
Transmitted Forces	Forces transmitted to spacecraft < 10 N	Prior designs have demonstrated undetectable force transmission	Phase 1 assessment
Specific Power	> 20 W/kg (converter only)	Predicted specific power is 21.6 W/kg	Phase 1 design, Phase 2 measurement
Size	Enable generator to fit within DOE shipping container	Conceptual generator design fits within DOE shipping container	Phase 1 design
Manufacturability	Proven and effective manufacturing approaches (goal)	Design relies on proven manufacturing processes	Phase 1 design
Instrumentation for flight converter	Long-life sensors not required (goal)	Current design only requires voltage comparator circuits	Phase 1 design, Phase 2 test
Performance measurement	Enable measurement of interface temperatures, alternator output, and rotational speed; enable disassembly for internal inspection	Design includes appropriate performance measurement instrumentation and inspection capability	Phase 1 design, Phase 2 test

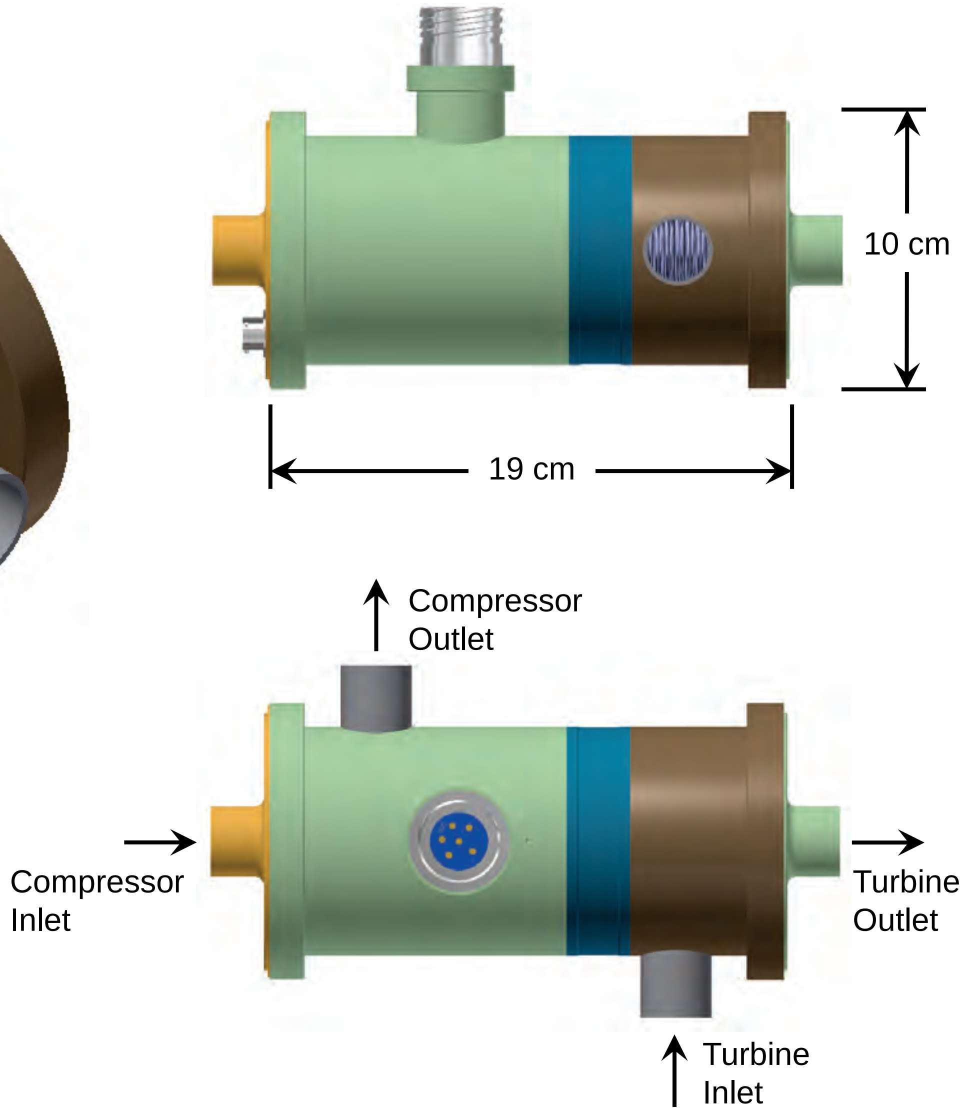
Turbomachine

Configuration

- Turbine-Alternator-Compressor (TAC) assembly
- Compressor, alternator, and bearings located at cold end of assembly
- Turbine located at hot end of assembly
- Hot and cold ends joined together by relatively thin metal structures
  - Provide rigidity with limited conductive heat transfer
- Space between hot and cold ends includes thermal insulation to limit radiation and convection
- Cold end must be cooled to remove heat from fluid drag, alternator losses, and hot-end transfer
  - Auxiliary radiator for spaceflight
  - Removable liquid-cooled heat exchanger for ground testing
- Materials
  - Turbine impeller is Rene-41 (UNS N07041)
  - Other hot-end materials are Inconel 625 (UNS N06625) and Rene 41
  - Bearings and alternator housing are phosphor bronze (UNS C54400)
  - Compressor impeller is Ti6Al4V ELI (UNS R56401)
  - Permanent magnet is samarium cobalt (S3069 from MCE)
  - Other cold-end materials are 316L stainless steel (UNS S31603) and copper (C14500)

Assembly Design





Rotor Assembly

- **Impeller diameters are 19 mm (0.75 inch)**
- **Shaft diameter is 6.4 mm (0.25 inch)**
- **Assembly includes dedicated thrust disk**
  - **Provides thrust capacity for 20 g static acceleration requirement**
- **Design speed is 2,730 rev/s (164,000 rpm)**
  - **Compressors with same impeller and shaft diameter operate at 380,000 rpm (four built previously)**
- **Rene 41 impeller brazed to Inconel 625 shaft**
- **Magnet epoxy-bonded inside hollow shaft**
- **Compressor impeller attached with fastener**
- **Mass is 19 g**

Bearings

- **Hydrodynamic gas bearings will support rotor assembly**
  - **Key feature that enables high specific power, maintenance-free operation, and long life**
- **Selected same journal bearings used in compressor for cryocooler on Hubble Space Telescope**
  - **Flexure-pivot tilt-pad design**
- **Plan to use modified version of thrust bearing from same machine**
  - **Double-acting spiral-groove configuration**
  - **Dedicated thrust disk is a new feature**
- **Bearing sizes and operating conditions fall within ranges of previously demonstrated values**
- **Analyses predict adequate operational margin**

Alternator

- **Serves as a motor during startup, then produces electric power once turbine is hot**
- **Configuration:**
  - **Two-pole samarium-cobalt permanent magnet epoxied inside rotor shaft**
  - **Three-phase wire-wound stator core with Alloy 48 laminations**
  - **Same magnet diameter and length as compressor on Hubble Space Telescope**
- **Electrical characteristics at full-power design-point conditions:**
  - **45.6 V line-to-line peak (18.6 V_{RMS} line-to-neutral)**
  - **6.4 A_{RMS}**
- **Predicted efficiency at design operating conditions is 95.6%**
  - **Resistive losses = 11.2 W**
  - **Core losses = 4.5 W**
  - **Fluid drag losses are accounted elsewhere**

Turbine Rotor Fabrication

- ❖ **Rene 41 will provide 20-year creep life**
  - **Analysis details presented later**
- ❖ **Fabrication process proven for prior projects**

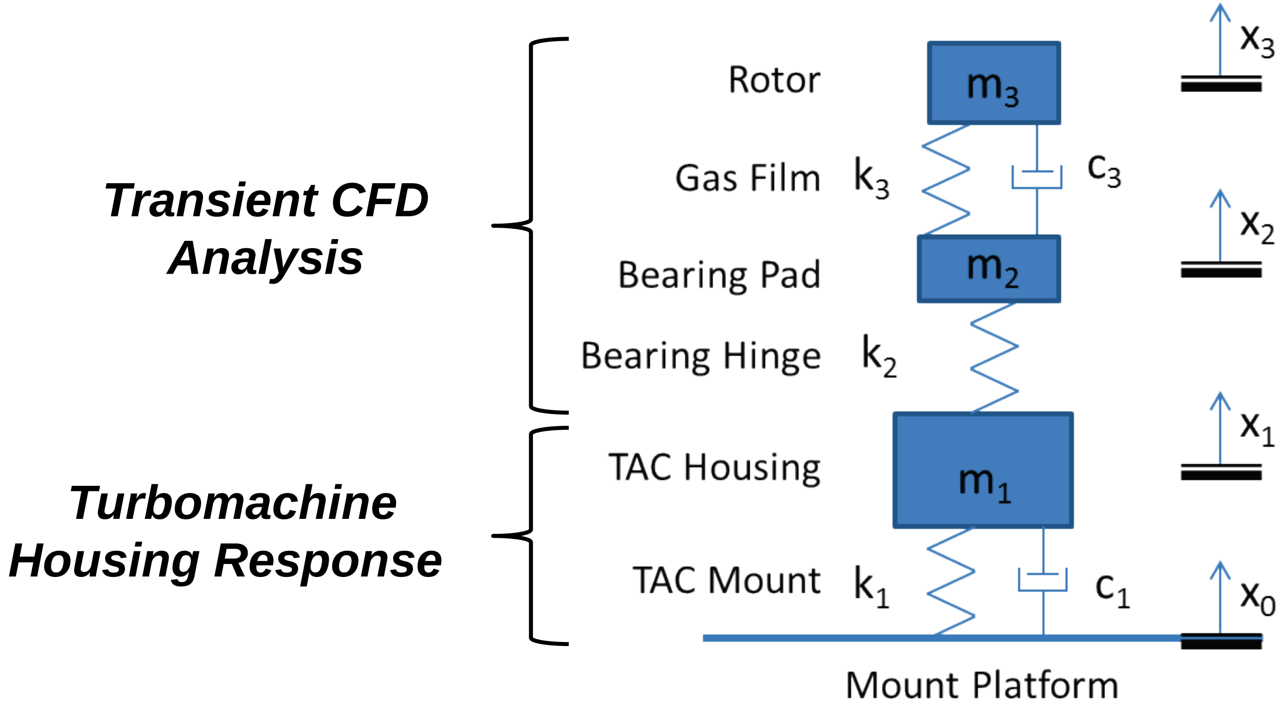
Turbine Impeller Creep

- Turbine impeller creep is critical life-limiting factor
- Considered René 41 (UNS N07041) and MAR-M-247
  - René 41 preferred
    - Easier to obtain
    - Easier to machine
    - Properties better understood
  - MAR-M-247 has greater creep resistance
- Goal is to prevent tertiary creep for 20-year operation life
  - 0.3% strain threshold for René 41
  - 2% strain threshold for conventionally-cast MAR-M-247
  - 1.7% strain threshold for microcast MAR-M-247
- Creep life goal achieved with René 41
  - Assumed worst-case creep performance
  - Significant safety margin regarding time, temperature, and stress

Bearing Dynamic Analyses

System Dynamics Model

- **Goal: To determine if there is contact between shaft/rotor and bearings during launch vibe and static acceleration**
- **Analysis approach**
  - **Time series input excitation**
  - **Lumped-mass response of turbomachine housing**
  - **Transient CFD analysis of rotor and bearing pad response**



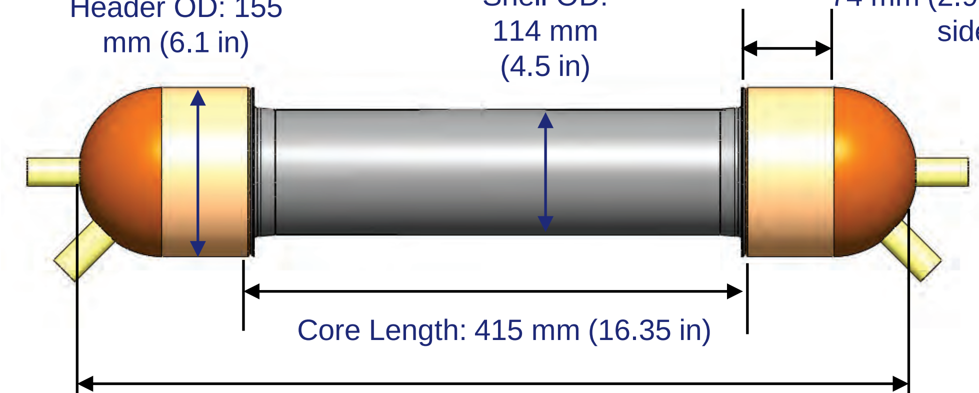
$|X_3-X_2|$ is quantity of interest

Summary of Results

- **Random vibration**
  - **Radial excitation (journal bearings)**
    - **Assessed two TAC mounts with different damping and stiffness characteristics**
      - **Mount has minimal impact on minimum clearance**
    - ***Contact is not expected to occur***
  - **Axial excitation (thrust bearings)**
    - **Assessed two TAC mounts with different damping and stiffness characteristics**
      - **Mount has minimal impact on minimum clearance**
    - ***Contact is not expected to occur***
- **Quasi-static 20G acceleration**
  - **Assessed one TAC mount (negligible change in input acceleration)**
  - **Radial excitation (journal bearings)**
    - ***Contact is not expected to occur***
  - **Axial excitation (thrust bearings)**
    - ***Contact is not expected to occur***
- ***Recommendations & path forward***
  - ***Increase minimum clearance for thrust bearing with minor design adjustments (smaller overall gap, reduced bias force) to increase margin to contact***
  - ***Dynamic testing during Phase 2 to corroborate modeling***

Recuperator

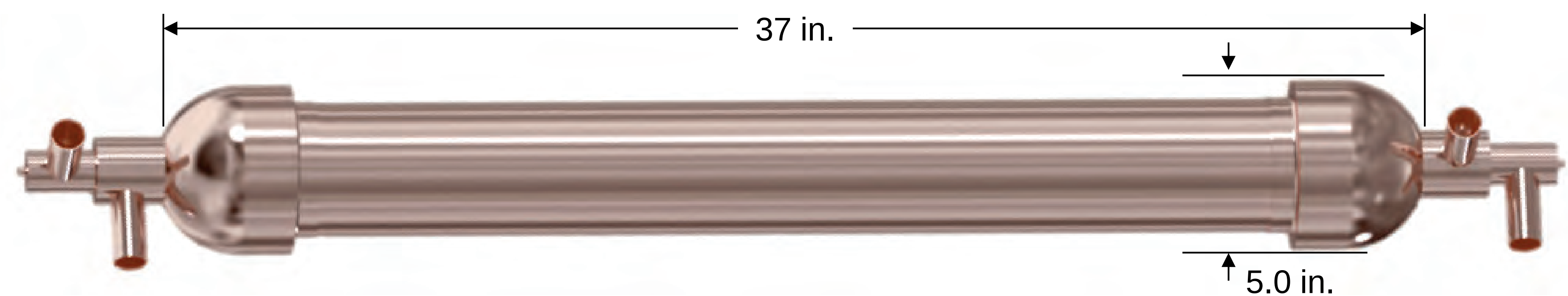
Recuperator Overview



Recuperator Design Details		
Design Parameter	Cryocooler	Converter
Inner Shell Diameter	49.5 mm (1.95 in)	No Inner Tube
Outer Shell Diameter	100 mm (3.94 in)	114 mm (4.50 in)
Tube Diameter	0.56 mm (0.022 in)	0.56 mm (0.022 in)
Tube Pitch	0.95 mm (0.037 in)	0.95 mm (0.037 in)
Tube Wall Thickness	0.05 mm (0.002 in)	0.05 mm (0.002 in)
Tube Length	800 mm (31.5 in)	564 mm (22.2 in)
Number of Tubes	6,642	11,922
Mass	9.1 kg	10.1 kg
Thermal effectiveness	98.8%	97.5%
Total Fractional Pressure Loss	1.6%	1.8%

Microtube Technology

- **Micro-shell-and-tube recuperators offer high-capacity alternative to legacy slotted plate recuperators in a cost effective design**
  - **Single module cost less than 25% of equivalent slotted copper stainless unit**
- **Cryocooler design**
  - **31.50 inch long core; 37 in. overall**
  - **5 modules in series**
- **Joint development effort**
  - **Creare – Design, fabrication and testing**
  - **Mezzo Technologies – fabrication and assembly**
  - **Edare – laser welding**

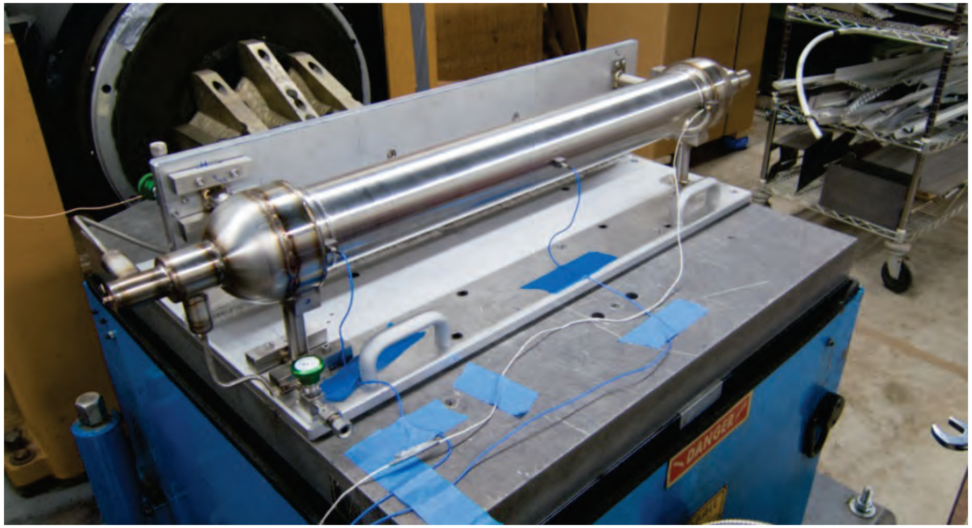


Development History

- Multiple technologies assessed on prior program and microtube recuperator selected for further development
  - Technology leverages existing technology at Mezzo Technologies
- Two recuperators (A & B) built on prior government and IR&D projects
  - Used legacy braze process to bond core
  - Measured performance was below design target due to a design flaw and defective braze joints in recuperator core
  - Recuperator B launch vibration tested and successfully passed GEVS requirement
  - Laser welding pursued on Creare IR&D to replace core brazing
- Microtube recuperator with laser welded core baselined for 20K, 20W program
  - First recuperator (C) built during design/risk reduction phase had problems with reliability of laser welds
  - Creare recommended and NASA approved an initiative to improve laser weld reliability
    - Improved geometric consistency of weld joint
    - Improved alignment of laser and tube
  - Resulting Recuperator D has 100% successful welds verified by leak test

20 K, 20 W Recuperator Structural Qualification Testing

- **Recuperator designed to meet NASA GEVS vibration requirements**
- **Recuperator B tested at 7.4 Grms in two directions**
  - **G-load consistent with 90 kg system mass for the cryocooler**
  - **Third direction was not tested due to symmetry**
  - **Accidental 30-minute tests were substantially longer than those required by GEVS (3 minutes)**
- **Recuperator passed the extended vibration test**



Successful vibration test corroborates structural modeling

20 K, 20 W Recuperator Thermal Performance Results

- ❖ **Ineffectiveness of Recuperator D (first production module) is close to target, and is being used in deliverable cryocooler**
  - **Target effectiveness is 98.8% at design flow rate**
  - **Measured effectiveness is 98.3% at design flow rate**
  - **Likely cause of shortfall traced to tolerance stack-up resulting in slight flow imbalance in core**
- ➢ **Recuperator E (second production module) was built with minor design changes relative to Recuperator D to reduce flow imbalance in core and improve performance**
  - **Thermal testing was performed on Creare IR&D**
  - **Measured effectiveness is 98.8% at design flow rate, consistent with predictions**
- ❖ **Three additional production modules built (5 total)**
  - **Nearly 100% successful welds**
  - **Testing will be performed at cryocooler level**

Performance modeling is mature and consistent with test results

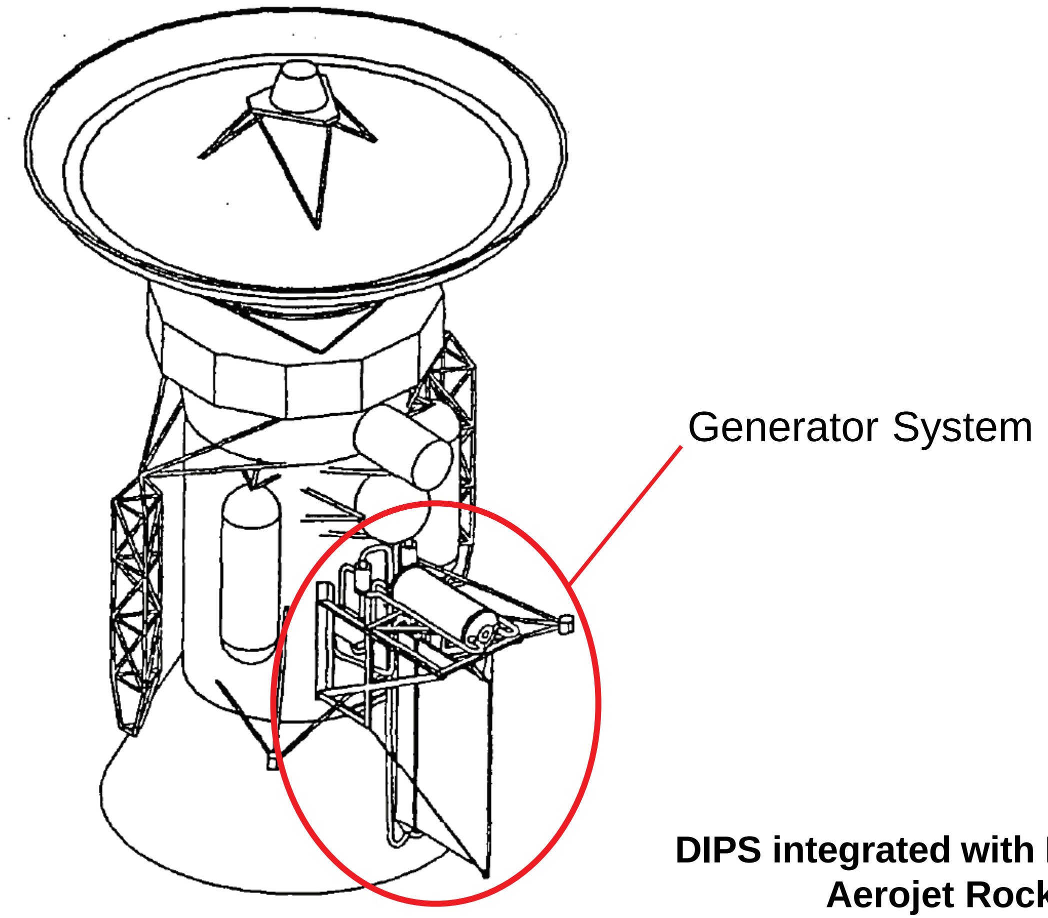
Extension to Power Systems

- **Microtube technology selected for RPS converter**
  - **Lower mass and volume than alternative technologies (e.g. plate-fin)**
  - **Spaceflight development already underway for cryocoolers**
- **Plan to use same materials and fabrication processes as for cryocoolers**
  - **All-welded assembly (no braze joints)**
- **Current design is very similar to cryocooler design**
  - **Shorter with larger frontal area to allow lower pressure losses**
  - **Solid cylindrical geometry instead of annular cylindrical geometry to reduce header complexity**
  - **Less restrictive flow headers to reduce pressure losses**
  - **Same size tubes and tube spacing**

Generator System Design
(Rocketdyne)

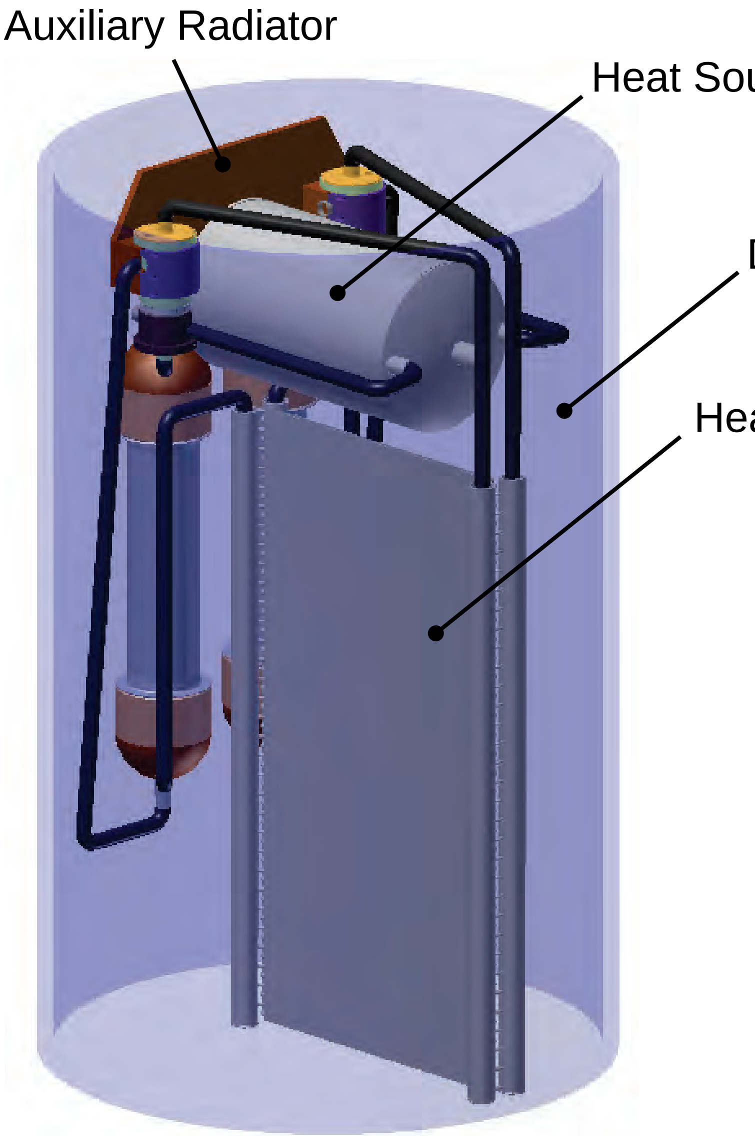
Conceptual Generator System Design

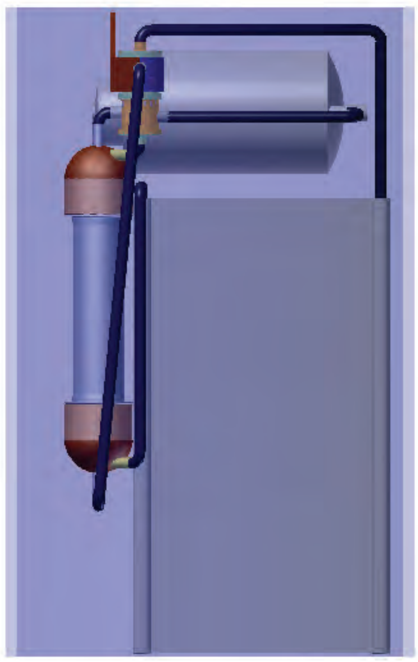
Creare/Rocketdyne design mimics DIPS configuration for JPL Mariner Mark II spacecraft with fixed two-sided radiator

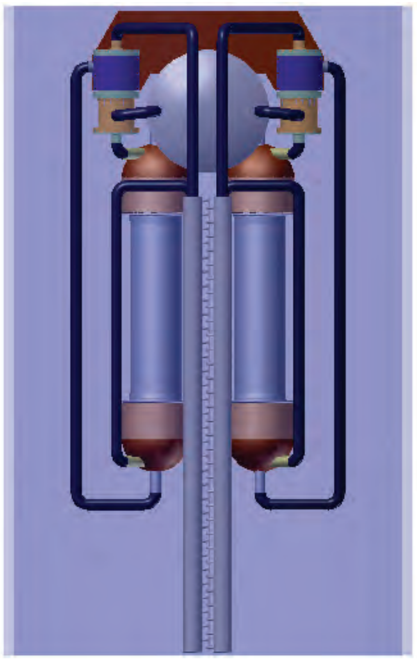


**DIPS integrated with MMII Spacecraft
Aerojet Rocketdyne**

Creare/Rocketdyne Conceptual Design







DYNAMIC POWER CONVERTERS
Heat Source Assembly and Heat Rejection Assembly
Phase 1 Final Review

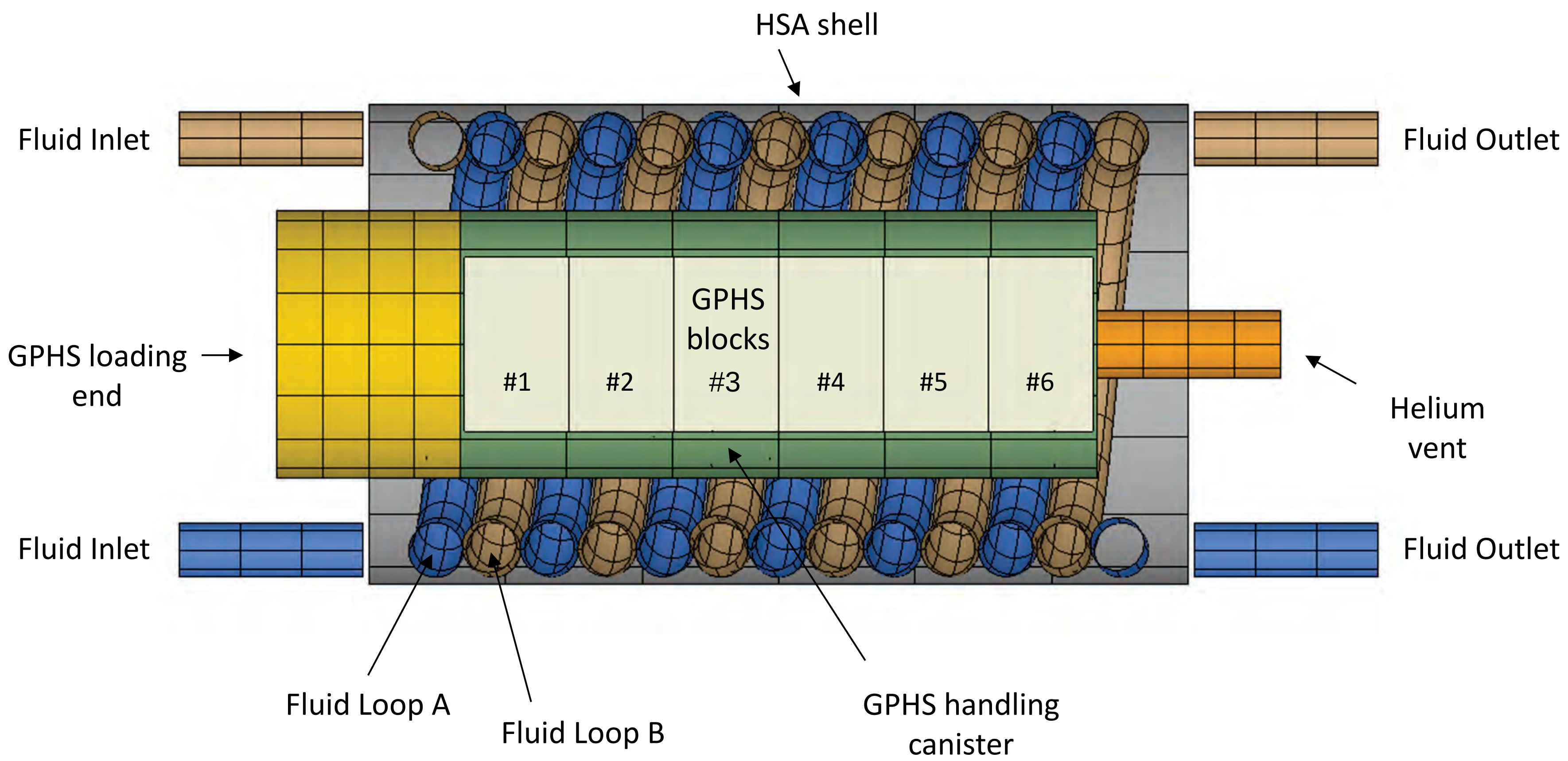
January 31, 2018

Prepared for:
Creare LLC
Contract Number: 89497

Aerojet Rocketdyne

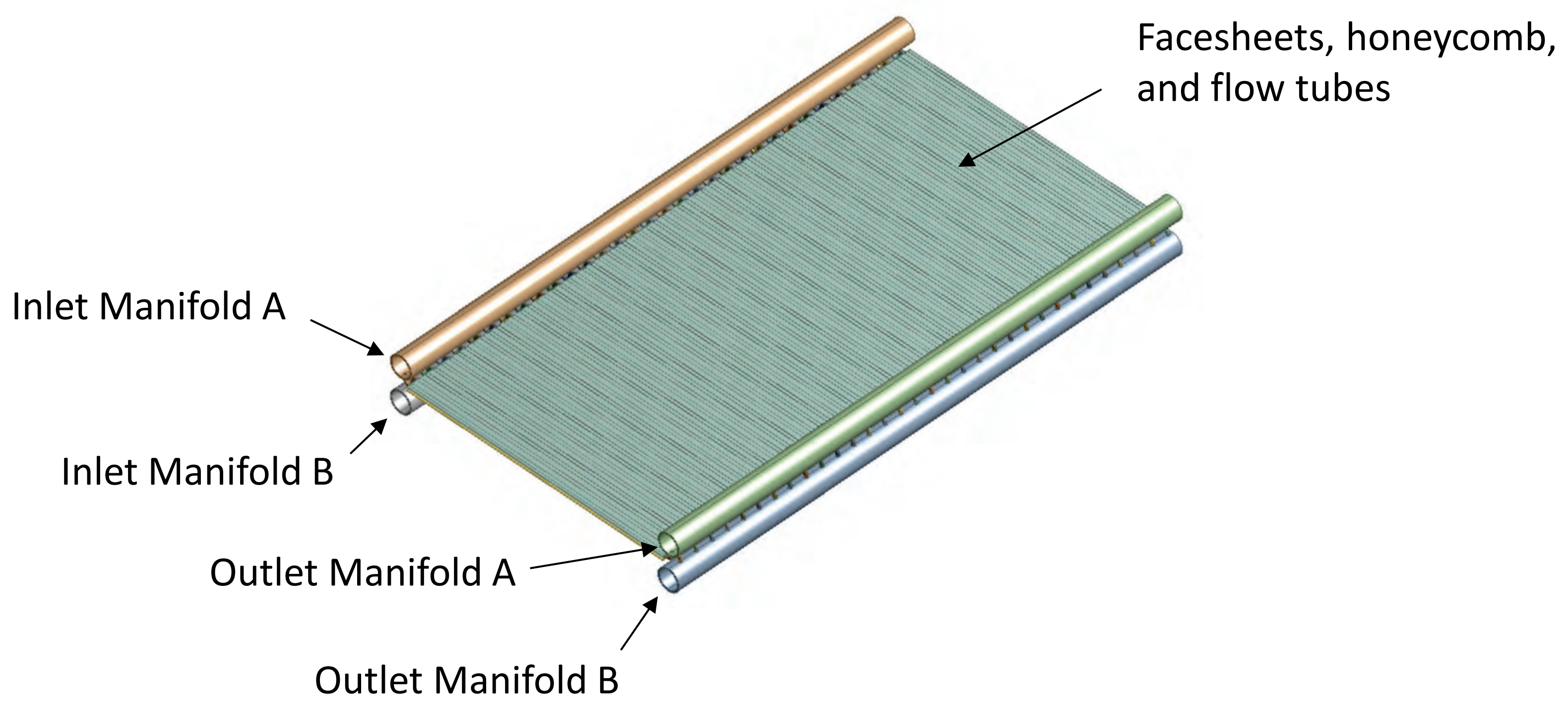
8900 DeSoto Ave.
P.O. Box 7922
Canoga Park, California 91309-7922

Heat Source Assembly
Design Concept



Heat Rejection Assembly
Design Concept

- **Gas flow radiator with two independent (A & B) loops for the HRA**
- **Analysis performed using SINDA/FLUINT analysis code**
- **Full power and half power cases assessed (sized for full power case)**



GPHS Thermal Analysis
(UNM-ISNPS)

CFD Simulation of Thermal Performance of General Purpose Heat Source Modules for Dual CBC Radioisotope Power System

Mohamed S. El-Genk and Timothy M. Schriener
Institute for Space and Nuclear Power Studies & Nuclear Engineering Department
University of New Mexico, Albuquerque, NM, USA

Phase 1 Final Review Meeting, 31 January 2018, NASA Glenn Research Center, Cleveland, OH

NASA Contract No. 80GRC017C0028, Creare – UNM subcontract No. 89495, 2017

Summary

- Results of 3-D thermal analysis, of stack of 6 GPHS module, coupled to HEX in HSA with Xe flow, demonstrate operation temperature margins
  - <u>One Coil</u> (CBC loop) full Power, Vac./ He in GPHS gaps:
    - Iridium cladding minimum surface temperatures:

      1,470.7 / 1,245.7 K (297.7 / 72.7 K above limit of 1173 K)
    - Aeroshell maximum surface temperature:

      1,269.7 / 1,225.1 K (103.3 / 147.9 K below limit of 1373 K)
  - <u>Two Coils</u> (loops) 50% Power, Vac./He in GPHS gaps:
    - Iridium cladding minimum surface temperature:

      1,473.4 / 1,252.5 K (300.4 / 79.5 K above limit of 1173 K)
    - Aeroshell maximum surface temperature:

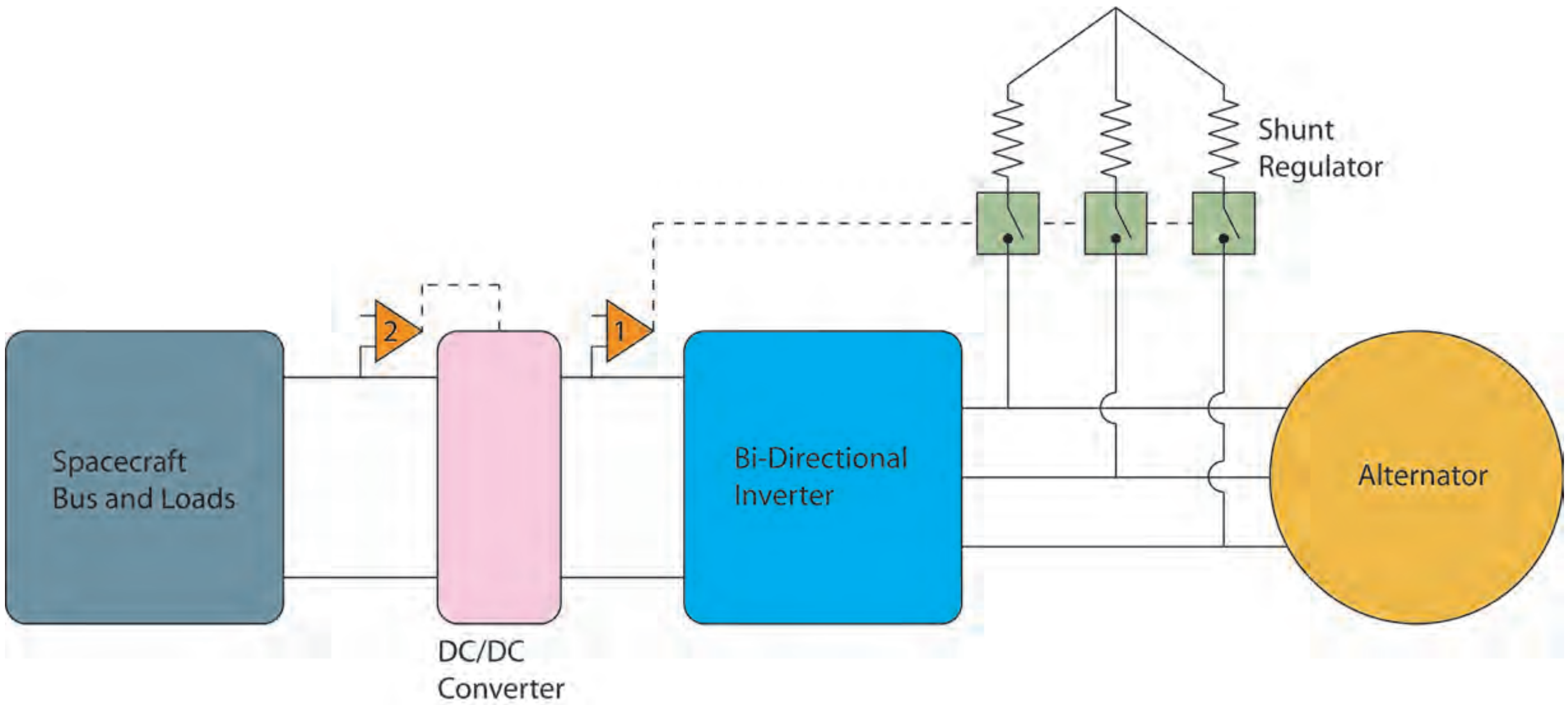
      1,271.0 /1,288 K (102 /145 K below limit of 1373 K)

Electronics and Controls

Approach

- Fundamental approach has been demonstrated by Creare and others
- Bi-directional inverter will control turbomachine speed
  - Provide motor power during startup
  - Produce regulated electric power during hot operation
- Bus voltage will be fixed by DC/DC converter
- Shunt regulator will dissipate excess power autonomously
  - Three-phase configuration connected directly to alternator leads
  - Resistors and cooling system sized to dissipate all power produced by converter
  - Configuration provides turbomachine over-speed protection
    - Loss of electrical load
    - Power electronics failure
- Laboratory-grade version planned for current project
  - Not designed for vacuum operation, radiation hardness, launch vibration, or EMI specifications
  - Not intended to be compact or lightweight
- Prior Brayton cryocooler electronics have been space qualified for HST
  - Acceptable vacuum operation and radiation hardness
  - Acceptable EMI emissions and susceptibility

Schematic Representation

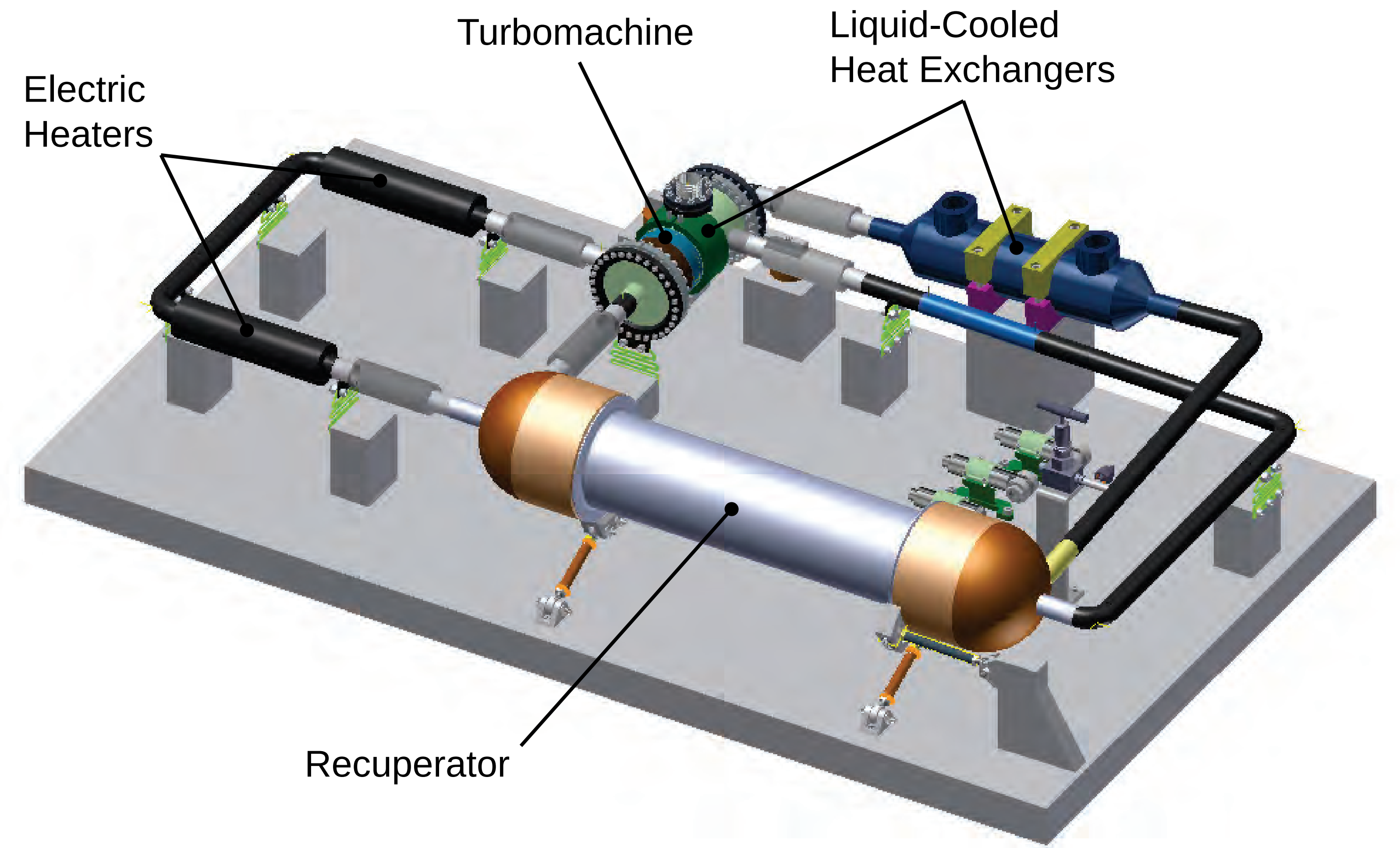


Controls

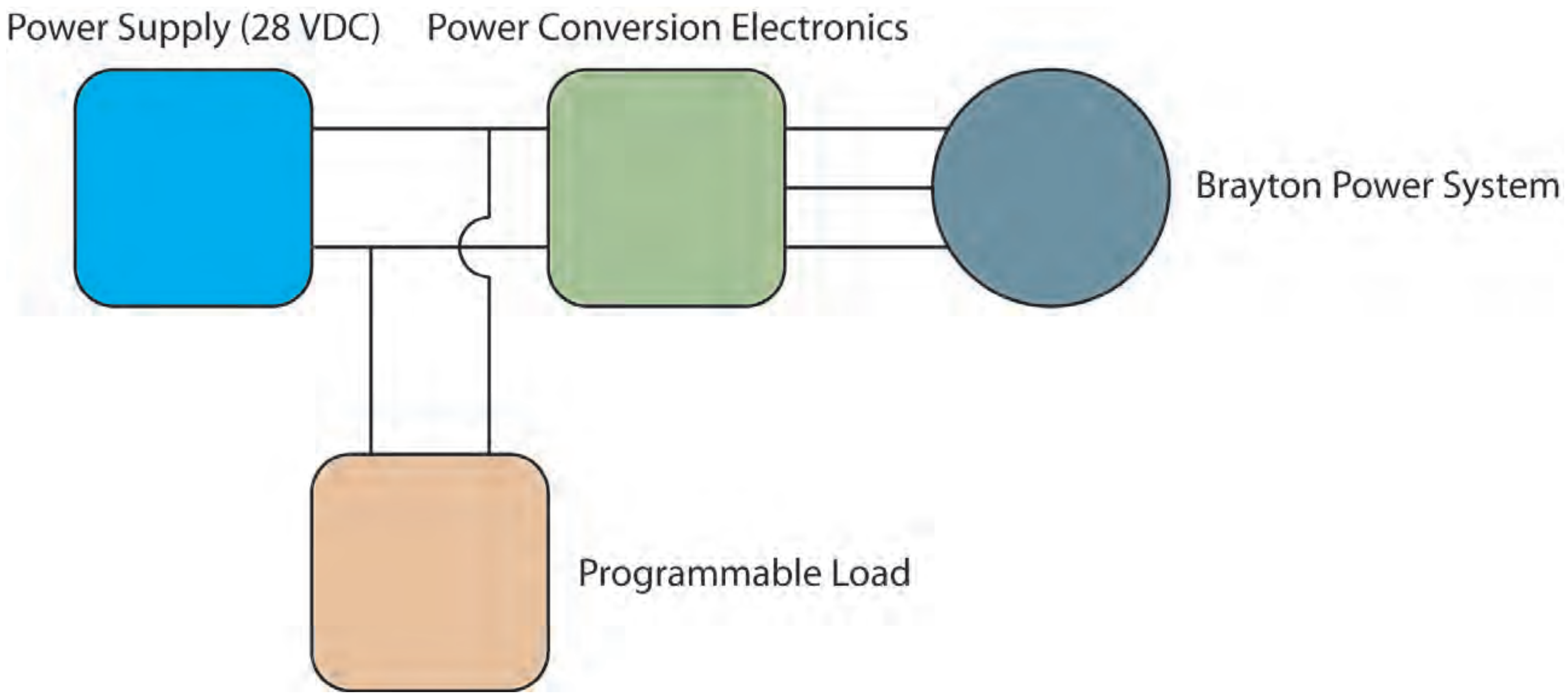
- Simple system
  - Scripted commands programmed into microcontroller
  - Voltage comparator circuits
- Autonomous sequence
- Laboratory version will provide autonomous shutdown when hardware safety limits are exceeded

Phase 2 Converter Assembly

Test Configuration



Power Conversion Electronics



Power Conversion Electronics

- Start turbomachine and control speed throughout operation
- DC supply provides power during startup
- Programmable load dissipates power once converter is hot
- Transition between power production and consumption is seamless
- Commanded speed can be adjusted freely within safe operating limits
- Key element is bi-directional inverter/rectifier with integral DC/DC converter

Emergency Shunt Load

- **Prevent turbomachine over-speed if primary control electronics fail to constrain speed properly for any reason**
- **Three-phase resistive load connected to alternator leads**
- **Normally-closed relays held open during normal operation**
- **Shutdown triggered automatically if rotor exceeds maximum allowable speed**
- **Direct action based on alternator voltage measurement**
  - **Alternator voltage directly proportional to rotor speed**
  - **Hardwired voltage comparator triggers shutdown**
    - » **Shunt relays close**
    - » **Commanded speed set to zero**
- **Response time will be less than a few milliseconds**
  - **FET rise and fall times are less than one microsecond**
  - **Predicted rotor acceleration rate with no load is 160 rpm per millisecond**
- **Loss of load combined with shunt failure <u>may</u> be acceptable**
  - **Preliminary conservative assessment indicates maximum speed is 228,000 rpm**
    - » **Less than resonant bending frequency and within bearing capabilities**
  - **Complete loss of load demonstrated previously by Sandia with sCO_2 Brayton system**
  - **More detailed analysis required**

Reliability and Robustness

Bearing Flexure Fatigue Analysis

- **Total number of cycles = 2,700 Hz * 20 years = 2x10^{12} cycles**
  - **Other Creare turbomachines have demonstrated this level**
- **Unable to find fatigue data for C54400 bronze**
  - **Similar alloys exhibit fatigue shown in figure below**
    - » **Dashed line represents 2x10^{12} cycles**
  - **Infinite fatigue strength is ~200 MPa for C51000 (similar to C54400)**
  - **Infinite fatigue strength > 100 MPa for all alloys shown**
  - **Maximum possible stress is 12 MPa (conservative limit)**

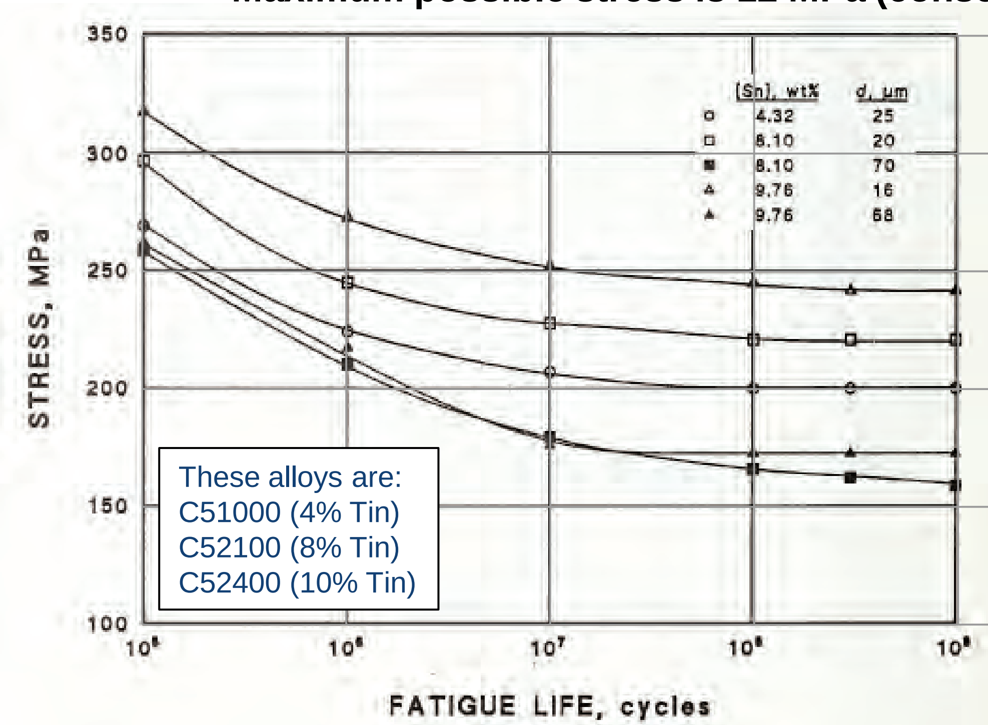


Table 11.3 Chemical compositions of phosphor bronzes

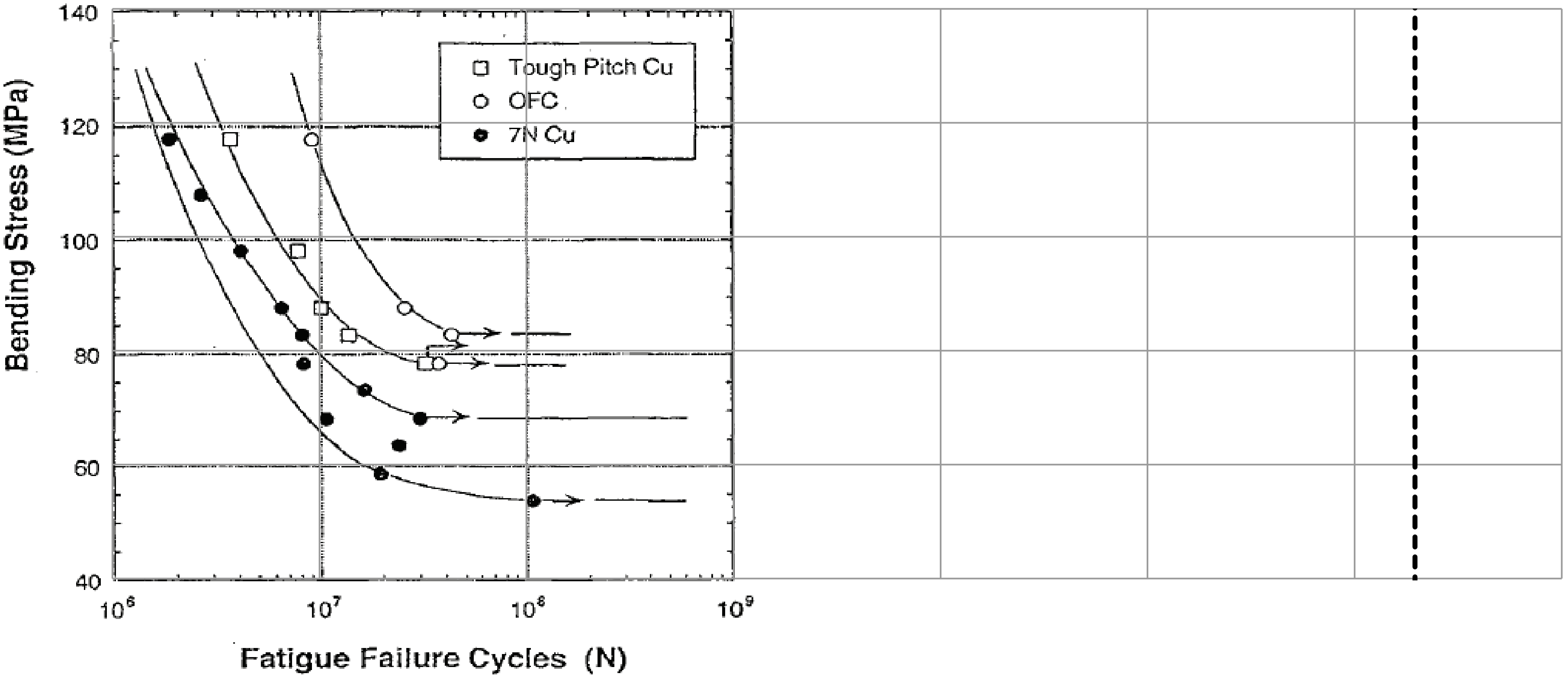
Phosphor bronzes						
Alloys	Chemical composition (wt%)					
	Pb	Fe	Sn	Zn	P	Cu
C50100	0.05	0.05	0.50–0.8	–	0.01–0.05	Bal.
C50200	0.05	0.10	1.0–1.5	–	0.04	Bal.
C50500	0.05	0.10	1.0–1.7	0.30	0.03–0.035	Bal.
C50700	0.05	0.10	1.5–2.0	–	0.30	Bal.
C50710	–	–	1.7–2.3	–	0.15	Bal.
C50715	0.02	0.05–0.15	1.7–2.3	–	0.025–0.04	Bal.
C50900	0.05	0.10	2.5–3.8	0.30	0.03–0.30	Bal.
C51000	0.05	0.10	4.2–5.8	0.30	0.03–0.35	Bal.
C51100	0.05	0.10	3.5–4.9	0.30	0.03–0.035	Bal.
C51800	0.02	–	4.0–6.0	–	0.10–0.35	Bal.
C51900	0.05	0.10	5.0–7.0	0.30	0.03–0.35	Bal.
C52100	0.05	0.10	7.0–9.0	0.20	0.03–0.35	Bal.
C52400	0.05	0.10	9.0–11.0	0.20	0.03–0.35	Bal.

Table 11.4 Chemical compositions of leaded phosphor bronzes

Leaded phosphor bronzes						
Alloys	Chemical composition (wt%)					
	Pb	Fe	Sn	Zn	P	Cu
C53400	0.8–1.2	0.10	3.5–5.8	0.30	0.03–0.35	Bal.
C54400	3.5–4.5	0.10	3.5–4.5	1.5–4.5	0.01–0.50	Bal.

Fatigue for Pure Copper

- Assuming pure copper should provide a conservative limit
- Dashed line represents 2×10^{12} cycles
- Infinite fatigue strength is ~50 MPa



Turbo-Brayton Converter for Radioisotope Power Systems FMECA Life and Reliability

Technical Information Meeting
January 31, 2018
NASA GRC
Cleveland, OH 44135

Ashwin Shah

Sest, Inc.

Subcontract No. 89494 Under Creare LLC's prime Contract No. 80GRC017C0028 with the National Aeronautics and Space Administration

Overview

- Completed Failure Modes Effects and Criticality Analysis (FMECA)
- Completed Reliability Assessment of the Turbo Brayton Convertor (TBC) and quantified TBC and it's subsystem reliability for a mission of 20 years
- Prepared Critical Items List (CIL) and Limited-Life Items List (LLIL) and identified the components that require detailed analysis, inspection, quality control and testing
- Reported analysis based on the set of drawings from the Creare LLC
- All contractual activities are complete

FMECA - RESULTS

- Updated the FEMCA Spreadsheet based on the comments from NASA
- Assigned Severity and Likelihood levels and completed Criticality Analysis
- Used Guidelines provided by NASA for severity and Likelihood Level assignments
- Basis to assign Likelihood Levels: (1) Analysis results (2) Reliability analysis and data available in the literature (3) Test Data (4) Experience (5) Expert Judgement
- Total of 73 important failure modes identified
- Total 46 (63%) Single Point Failures (SPF)
- Majority of the SPF are structural related and mostly due to creep

Reliability Analysis Results

- Input probability of failures for the Critical Items List (CIL) and Limited-Life Items List (LLIL) used:
  - Are very conservative
  - Backed up by deterministic analysis results from Creare
  - Probability of failures for CIL and LLIL are expected to be much lower than what is used which will improve the reliability of the overall system
- Quantified the reliability of TBC during 20 year mission 97.35%

Reliability Analysis Results
(Continued)

System / Subsystem	Probability of Failure	Reliability
TBC Overall System	2.3630E-02	97.637%
Hot End Components	6.5480E-03	99.345%
Shaft Assembly	9.5200E-03	99.048%
Stator Assembly	3.4630E-03	99.654%
Cold End Components	1.7150E-03	99.829%
Power Pass thru	1.7850E-03	99.822%
Recuperator	1.0510E-04	99.989%
Journal Bearings	3.5030E-04	99.965%
Thrust Bearings	3.5030E-04	99.965%

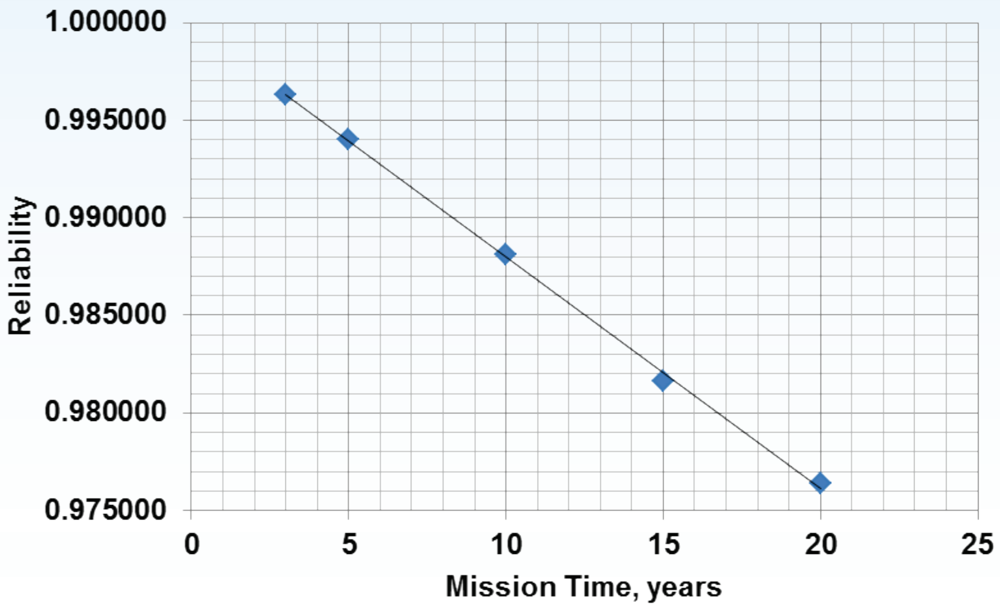
Reliability Analysis (Importance Measure)

- Contribution to the Probability of failure
  - Structural Creep related variables 44.52 %
  - Structural but non-creep related variables 39.04%
  - Rest of variables 16.44% - but individual variable contributions are very small
- Prognosis to improve creep related and non-creep related structural failure probability is extremely high
- With the advanced analysis, design and test the creep and structural reliability can be improved easily and therefore the TBC reliability

Reliability vs Mission Time

- As the mission time increases the reliability decreases

Mission Time (years)	3	5	10	15	20
Reliability	0.996294	0.994039	0.988110	0.981600	0.976370



Robustness

- Possible variations that could impact TBC performance, efficiency and integrity are temperatures, pressure and launch vibrations
- Speed of the turbo machine could go higher than the design speed due to loss of electrical load and controller and shunt resistor failure. However, controller and emergency shunt resistor will prevent such an event
- Machine bearings have significant margin to operate at speeds higher than design
- TBC Design for the system and its components have fairly big margin between actual response value and it's respective allowable. Therefore, any unforeseen variation in the design parameter is unlikely to impact its reliability and life
- Further recommended fine tuning of the design, inspection, QA and testing shall add to the robustness of TBC design, life and reliability

Summary

- FMECA for the TBC has been completed.
- Reliability Analysis is completed
- Based on backup analyses and test data information from Creare, evaluation and judgment, majority of the single point failures (SPF) have been designed out and associated reliability is deemed to be higher than what is predicted

Conclusions

Conclusions

- Brayton converters are attractive for space power systems
- Creare team has experience and capabilities to enable long-life systems suitable for spaceflight
- RPS program provides critical demonstration opportunity
- Team is excited, motivated, and ready to demonstrate prototype converter